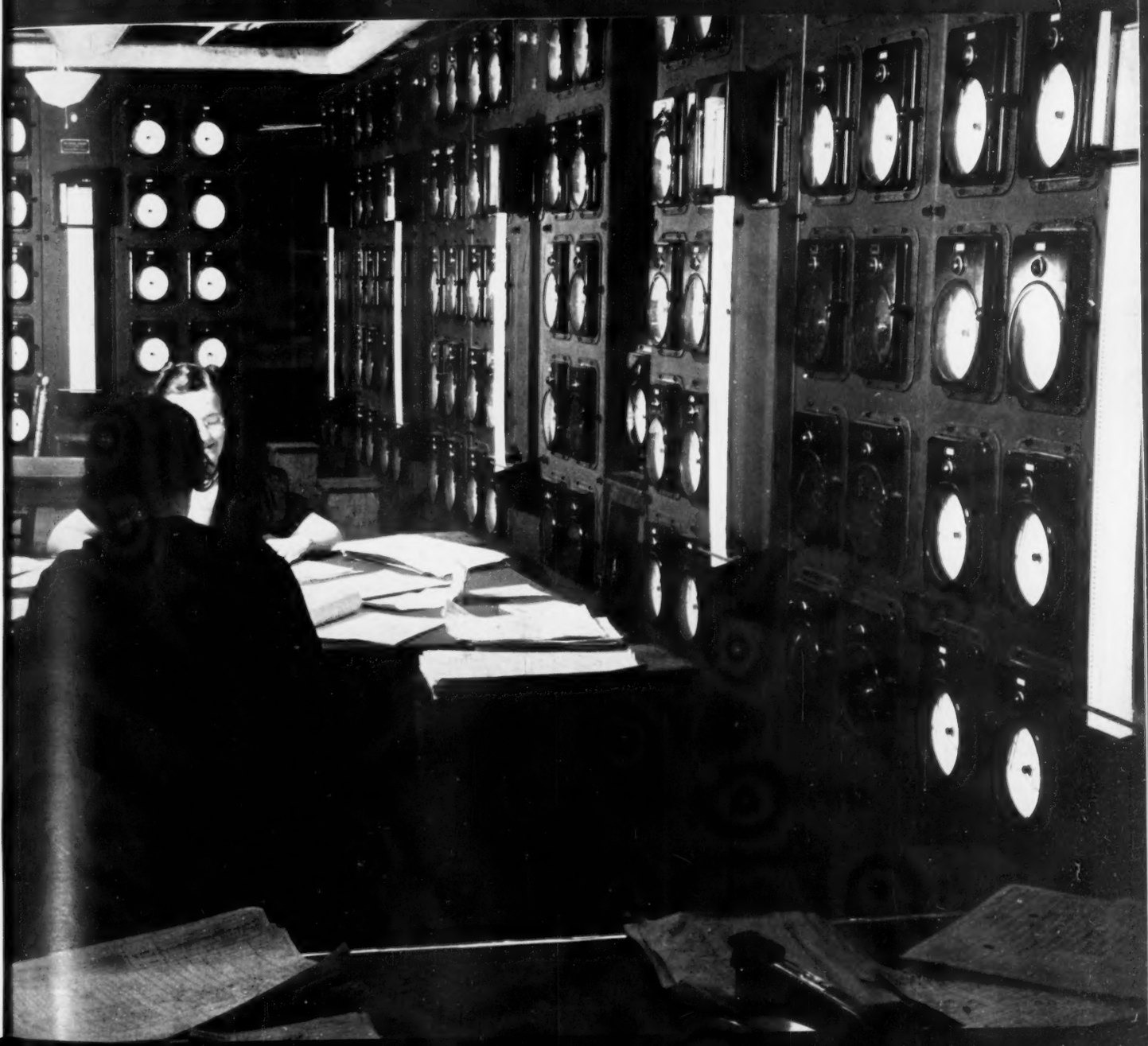
Instruments

THE MAGAZINE OF Measurement and Control

Vol. 12
AUG.
1939
No. 8



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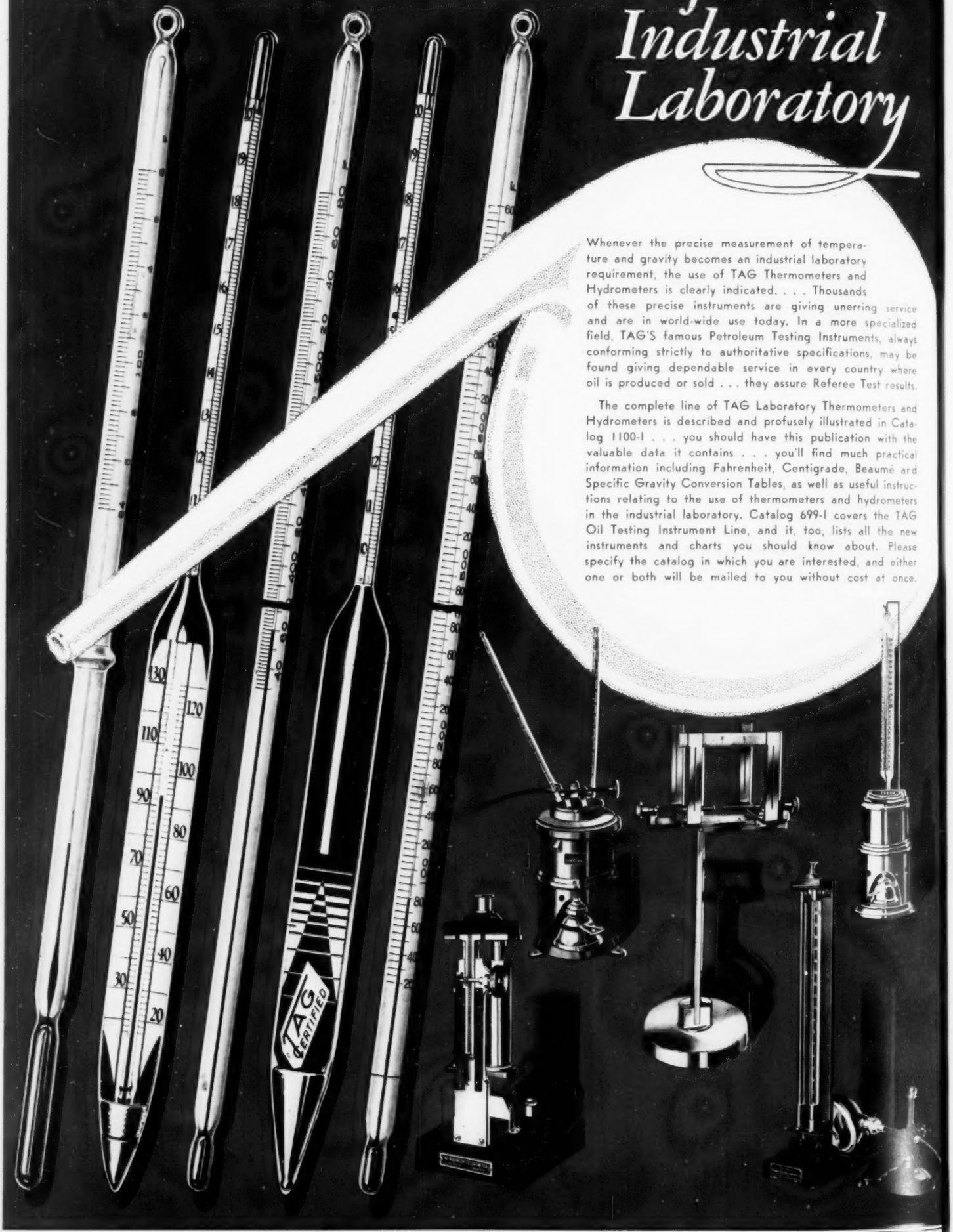

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Instruments
The Magazine of Measurement and Control

Vol. 12 AUGUST 1939 No. 8

FRONT COVER: Centralized time recorders, Revere Copper & Brass, Inc., Rome, N. Y.
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Published Monthly on the 15th by
THE INSTRUMENTS PUBLISHING COMPANY
1117 Wolfendale Street, Pittsburgh, Pa.

RICHARD RIMBACH, Managing Editor
M. F. BEHAR, Editor

BRANCH OFFICES

Boston: James Condon, 25 Brimmer St. (Lafayette 9769)
New York: R. K. Farnham, 118 E. 28th St. (Lexington 2-4637)
Chicago: William Farnham, 201 N. Wells St. (Andover 4180)
Cincinnati: Harold W. Haskett, Keith Bldg. (Main 4481)
Cleveland: Burdette Phillips, 405 Erie Bldg. (Main 9646)

Annual Subscription: U. S. $2.00. All other countries $3.00 *payable in advance* (remit by New York draft).

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Entered as second-class matter January 26, 1932, at the post office at Pittsburgh under the Act of March 3, 1879.

Instruments

THE MAGAZINE OF *Measurement and Control*

M. F. BEHAR, Editor

SEVERAL unmistakable signs indicate that the importance of instrumentation is recognized to such an extent that there is a shortage of qualified instrument men: instrument makers, instrument inspectors, instrument maintenance men, instrument mechanics and professional instrument engineers. The following official communication speaks for itself:

WAR DEPARTMENT
AIR CORPS—MATERIEL DIVISION
Office of the Eastern District Representative
90 Church Street, New York, N. Y.

To the Editor:

This office would like to bring to the attention of qualified instrument makers the fact that the United States Army Air Corps, during its current building program, has vacancies for the temporary employment of inspectors of aircraft instruments and similar precision apparatus.

The United States Civil Service Commission has authorized the Air Corps to make these temporary appointments pending the establishment of a Civil Service list of eligibles; and those who may be selected for temporary appointment will be paid $2300 yearly and given an opportunity to compete in the regular examination when it is held for permanent appointments.

Citizens of the United States, having six or more years in the actual making of fine instruments to micrometer precision, are invited to write for information to the Air Corps District Manager, Room 1216, 90 Church Street, New York City. Those whose experience has been that of merely assembling will not qualify.

For the Eastern District Representative
J. A. McDONNELL
District Manager, Air Corps
Eastern District

July 19, 1939

Almost in the same mail as the above, we received the July issue of the *Boeing School News*, published by the Boeing School of Aeronautics, Oakland, Calif. The leading article deals entirely with "The Instrument Mechanic." It emphasizes his high requirements which include:

> . . . Imagination and common sense so that he may continually devise solutions to new problems and, at the same time, be certain that his work constantly fulfills the rigid requirements of accuracy and permanency necessary in the safe operation of aircraft.

The article suggests that in spite of the word "mechanic," jobs are both highly regarded and well paid. Opportunities for advancement are mentioned. Boeing School graduates who specialized in instruments are now serving air lines as managers or as assistant managers of instrument departments and as installation foremen.

Within a few days of the receipt of the above, *Instruments* learned for the first time that since last January a group of instrument men in the Pittsburgh district have been meeting and named their group The Society of Instrument Engineers. These men have been organizing the nucleus of a *professional* engineering society. Their leader, Frank C. McGough, recently spent an evening at your editor's home and we find that he combines an intense enthusiasm for Instrumentation with absolute confidence in the future of the profession of instrument engineering, and personal qualities of leadership. We mentioned to Mr. McGough that similar groups of instrument-minded engineers may be in existence in other parts of the country, and he replied that if any such groups exist, the Society of Instrument Engineers desires to get in touch with them with a view to organizing a national society. His home address is 3 Buffalo St., Pittsburgh.

Before *Instruments*, a professional society of instrument users in industry would probably have been premature. Even if the founder had possessed the charm and leadership of Frank C. McGough, his task would have been formidable. "Would have been"? It *was!*

We well remember, at a gathering of instrument-minded engineers about fifteen years ago, one engineer present saying "Not more than twenty men in all this country would join an instrument society, because there aren't more than a hundred or so trained instrument specialists in all instrument-using industries."

Since 1928 *Instruments* has been "creating" instrument mechanics, instrument maintenance men and professional instrument engineers. In the last five years or so, there has been a growing disparity between the rate of installation of instruments and the rate of training of instrument men of all classes. Many engineers whose duties involve the selection and supervision of instruments now take pride in calling themselves instrument engineers. No wonder that they think of themselves as professional instrument engineers. No wonder they are organizing on a professional basis.

The familiar remark that "there are too many societies in America" is true, but equally true is the imminent fulfillment of the prediction which once aroused ridicule: "I confidently predict the recognition of Instrumentation as a distinct branch of engineering and as a distinct field of industrial management . . . instrument courses in the majority of technical schools . . . a nation-wide Society . . . and all the panoply of an established, organized, esteemed profession."

Now for a remarkable coincidence: One of the purposes which led Frank C. McGough and his friends to organize themselves was their intention to hold a series of technical meetings in order to ground themselves thoroughly in the science of instrumentation. At about the same time, such a course was being prepared; and it will be given at the Carnegie Institute of Technology. The announcement of this course is printed below and we hope that many readers in this district will not only avail themselves of it but bring it to the attention of likely candidates.

Please post on Bulletin Board

CARNEGIE INSTITUTE OF TECHNOLOGY
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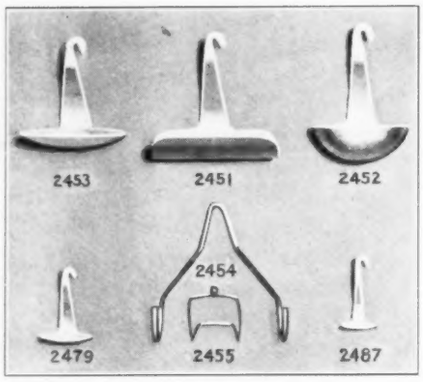
Evening Course in Instrumentation
1939-1940

In order to fill a demand definitely manifested by industries in the Pittsburgh district, a thorough course in Instrumentation has been added by the Metallurgical Department of the Carnegie Institute of Technology Evening School for the year 1939-1940. Major M. F. Behar, author of several engineering textbooks on industrial instruments and their application in the manufacturing and processing industries, and editor of the magazine *Instruments*, will be in charge of the course.

Twenty-eight evening sessions of two hours each make up the calendar of this course, from October 2 to May 20. Nineteen sessions have been allocated to visiting lecturers —chief engineers and research directors of companies specializing in the manufacture and application of recorders, meters, telemetering systems and automatic-control systems.

Registration for this course will be held only on two dates: Monday and Tuesday evenings, *September 25 and 26, from 7 to 10 p.m. in the Gymnasium.*

The sessions of the Course will be held on Monday evenings from 7:30 to 9:30, from October 2 to May 20.



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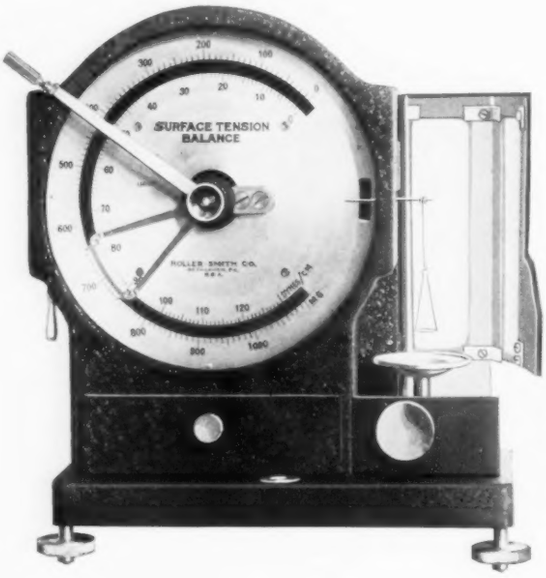

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Measurement and Analysis of Noise and Vibration

By DANIEL SILVERMAN

Formerly Assistant Professor of Mechanical Engineering, University of California; now Geophysicist, Tulsa, Okla.

FOREWORD

By M. F. Béhar, Editor *Instruments*

MOST frequently quoted of sayings by great scientists is Lord Kelvin's on the importance of quantitative measurements as against mere observations. When he died, Lord Kelvin must have regretted that so many observable phenomena of acoustics and vibrations were so dimly understood because they could not be measured. If he were alive today he would be thrilled by the appearance of such a book as Dr. Silverman's—a milestone signalizing at last that these phenomena are all measurable by *ad hoc* instruments.

As has been the case in other provinces of instrumentation, industrial advances intensified the need of quantitative measurements, Science met the challenge by discovering reproducible effects whereby properly-scaled instruments could be constructed, Technology built the various prototype instruments and applied them, Industry learned to use them so well that it re-defined its needs, whereupon Physics caught the ball and passed it to Engineering which ran down the field with Physiology, Psychology, Industrial Hygiene and other team-mates—all for the public good.

In other words, science has given us the Industrial Age with its mixture of good and bad—one of the bad gifts being noise. Joint efforts on the part of numerous groups have at last given us noise-measuring and -analyzing instruments. The growing use of these instruments has made us all more intelligently noise-conscious. Parallel with reduction in sources of noise is the present increase in the number of new acoustic products and in the perfection of old ones. Astonishing progress has been made, for example, in what were called ear-stoppers and are now called "ear defenders," Dr. V. O. Knudsen and the Mine Safety Appliances Co. having recently completed a long program of instrumentized research on this single subject! The point is this: In Lord Kelvin's day, the factory age was threatening to deafen many workers and the old-style ear plugging devices weren't any good; today, thanks to the availability of a complete series of types of noise and vibration instruments and to the extension of knowledge of their possibilities and limitations: (1) noises and vibrations can be minimized at their sources; (2) the harmful effects of insuppressable noises can be totally eliminated and—perhaps most important—you and I and Bill and Mary *know* that it's so!

SECTION 1
INTRODUCTION

WITHIN the past decade a renewed and greatly increased interest has become evident in the science of acoustics, and more especially in its practical aspect, the problem of noise and noise elimination. Heretofore, acoustics has been a branch of theoretical physics, but with the development of the electronic arts, acoustics has become part of the engineering field, and today, acoustical engineering is an important part of our everyday life.

This change has stimulated the development of new and novel types of instruments for the study of noise, and the appearance of articles in the technical press which have fostered a wide response among all classes of people.[1] Theaters and auditoriums, as well as homes and offices, are being planned and treated for the reduction of noise, and machines of all sorts are being designed, built, sold, and purchased with a decided regard for the noise that they produce.[1] But it is not only in the planning of new structures that quietness is being sought, but also in present-day mechanical and electrical equipment. Noise surveys[2] have been made to determine the most disturbing elements of our daily life, and efforts are being made to modify equipment, or to isolate and insulate structures, so that quieter living conditions may be obtained. And as the science of acoustical engineering progresses, it becomes as easy to predict the reverberation time of a room, or the noise level of a vehicle, or the frequency response of a sound system, as it is to predict the performance of an electric motor.

In addition to the practical effects of noisy surroundings, there are more subtle psychological and physiological effects on persons subjected to noisy surroundings that have become the objects of considerable study. The qualitative aspects of these effects are of course evident to most persons, but actual measurable effects of importance have been identified and studied by many experimenters in this work. Reductions of noise of easily obtainable amounts, in one instance,[3] have been the cause of increased efficiencies up to 9%, reductions of errors of from 30 to 50%, reduced employee turnover of up to 50%, and a decrease of absences of 37%. Other examples confirm these data. Laird[4] indicates that the reduction of sound intensity by 10 db* has increased the output of a group of workers by as much as 12%. Other workers[5] have also found that a decrease in noise level has increased the volume and the accuracy of work done by persons subjected to noisy surroundings. This is particularly true when the work is largely mental.

In addition to the economic advantages to be gained by the reduction in noise, there are distinct advantages to be gained by the persons themselves in the form of improved mental and physical health, reduced nervousness, and increased well-being. It may happen that the persons become so accustomed to their noisy surroundings that they fail to realize the intensity of the noise, which would be noticed immediately by one being subjected to the same conditions for the first time. This apparent lack of notice is the result of forced concentration, and is the cause of lost energy and increased fatigue.

Noise is a by-product of many types of mechanical and electrical machines and of human activity. There are few cases where the production of noise is the desired result of the application of power, except in the signaling field. Noise unintentionally produced is evidence of mechanical inefficiency and can be reduced by the removal of the cause of inefficiency. Since the amount of energy in acoustical waves is generally small, the actual energy lost in this form is insignificant. The important fact is, that the noise is evidence of dissipation of energy in other forms. The sensitivity of the ear, and of acoustical instruments in general, is such that the losses of a machine made evident by noise can be detected more readily by means of these instruments

Numbered bibliographical references will be found at the end of each Section.

*The decibel (db) is a logarithmic unit representing ratios of energies. See Appendix I on the decibel scale.

than they can by means of power measurements on the machine. The ear, of course, is a good acoustical instrument, and the buyer or the user of mechanical or electrical equipment makes use of his ears unconsciously, or intentionally, in judging the quality of the machine. Consequently, any change in design made as a result of acoustical instrumental measurements must be in agreement with aural observations. Quiet operation is a sign of efficient design and correct construction.

The advance in technique of control and reduction of noise, is the result of, and is dependent upon, the availability of instruments for the measurement of noise. There has been a great activity among makers of acoustical instruments, and there have appeared on the market numerous types and designs of instruments for the measurement and the analysis of noise, the review of which forms the purpose and the substance of this work.

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SECTION 2

ACOUSTICAL BASIS OF SOUND METERS.

The number of purely acoustical instruments is extremely limited. However, the state of instrumentation in the electrical field is well advanced, and it has been possible to make use of a great number of electrical instruments, and to adapt them to the field of acoustics. These electrical instruments, since they are used in conjunction with acoustical elements for the measurement of acoustical magnitudes, may properly be called acoustical instruments. They are applied to circuits in which the currents or voltages are derived from acoustical waves by means of one or more electro-acoustical components, or transducers.

There are, in general, two types of instruments for the study of noise: those that deal with the overall effect, or total sound meters, and those that deal with the components of the acoustical waves, or the analyzing instruments. In the case of the total sound meter there are a number of physical magnitudes associated with acoustical waves which are capable of direct measurement, and which serve as the basis of a number of indicated quantities which are of practical interest.

Sound waves passing through air cause periodic variations in pressure, temperature, density, and particle velocity. Any acoustical instrument for the study of sound must contain at least one element responsive to one or more of these effects. This element is the microphone, and is most commonly designed to measure the sound pressure, or the particle velocity, variations. Of the other effects, fluid density does not lend itself easily to measurement, but fluid temperature may be taken as an index of sound intensity, and has been measured by means of thermocouples and high sensitivity amplifiers.[1]

Starting with a pressure- or velocity-sensitive microphone, an instrument must be designed that will give one or more of the following readings which are used in the study of noise:[2]

1. Sound intensity,
2. Sound intensity level,
3. Sensation level,
4. Sound pressure,
5. Sound pressure level,
6. Weighted sound pressure level,
7. Loudness,
8. Loudness level.

Of these eight, sound pressure is the only one capable of direct indication by a microphone. This is the root-mean-square variation, from the mean, of pressure in the medium. Sound pressure level is a magnitude which can be easily indicated by an instrument whose microphone is sensitive to sound pressure. It is a logarithmic or decibel* scale, expressing the ratio of the actual sound pressure to a reference value (taken as 0.0002 bar†). The pressure level in decibels, is defined as 20 times the logarithm to the base 10, of the ratio of the actual pressure, P, to the reference pressure, P_0.

The intensity in a sound field is the rate of flow of energy, in the specified direction, through a unit area normal to this direction, at the point. The intensity may be expressed in units of ergs per second per square centimeter, or in watts per square centimeter. In the case of a plane or spherical free wave of effective sound pressure, P, dynes per square centimeter, where the velocity of propagation of the wave in the medium is c centimeters per second, and the density of the medium is ρ grams per cubic centimeter, the intensity in the direction of propagation is given by:

$$I = P^2/\rho c$$

This holds for other than true plane or spherical waves for points near the source, when the source is small. The reference intensity is standardized at 10^{-16} watts per square centimeter, which, in a plane or spherical progressive sound wave in air corresponds to a root-mean-square pressure, P, given by:

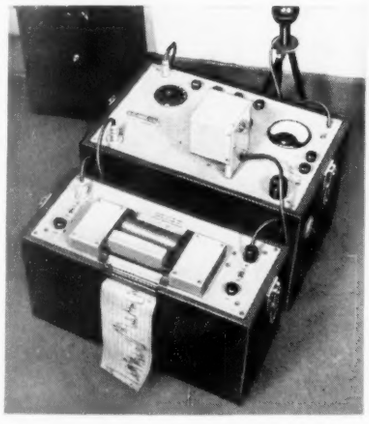
$$P = 0.000207\sqrt{\frac{H}{76}}\cdot\sqrt{\frac{273}{T}}$$

where P is in dynes per square centimeter, H is the height of the barometer in centimeters, and T is the absolute tem-

*The use and justification of the logarithmic unit, or decibel (db) is discussed in Appendix I.

†The bar is defined as a pressure of one dyne per square centimeter.

Have you an Acoustic Problem in YOUR industry?



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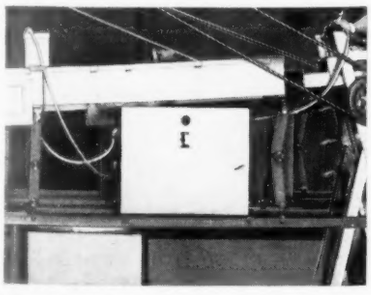

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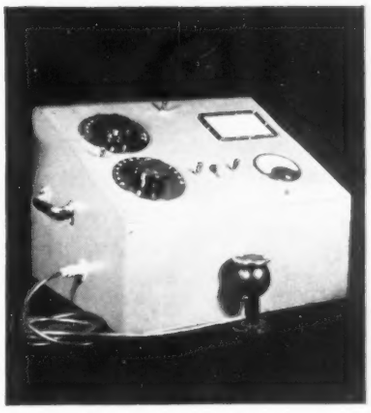

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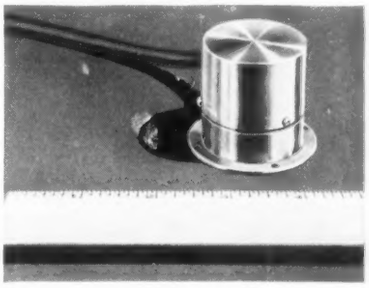

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perature. At 20° C. and 76 cm., P is 0.000204 dynes/cm.^{2}. Sound intensity level is the expression of intensity on a logarithmic scale, in decibels, above a base value of 10^{-16} watts per square centimeter. Sensation level is a logarithmic scale of intensity, in decibels above threshold, at a given frequency. For any one frequency this quantity serves as an approximate loudness scale.

Loudness[3] values are a series of numbers such that for every sound, pure or complex, there is an appropriate number expressing its loudness. Larger numbers represent louder sounds. These numbers are derived from subjective measurements, and are used in the formula of Fletcher and Munson[3] for the computation of the loudness of complex sounds, in which certain tones are subject to masking by others. Masking is the phenomenon by which sounds of different pitch can effectively hide or mask the presence of other sounds. The masking of a given tone by sounds of lower pitch is greater than that by sounds of higher pitch. No known meter can be calibrated to read directly in loudness for all types of sounds, particularly where there is masking, although for pure tones this is quite possible. Loudness level is expressed as the intensity level of an equally loud 1000-cycle free wave. This is, of course, a subjective comparison, and the judgment of a number of observers must be taken and averaged.

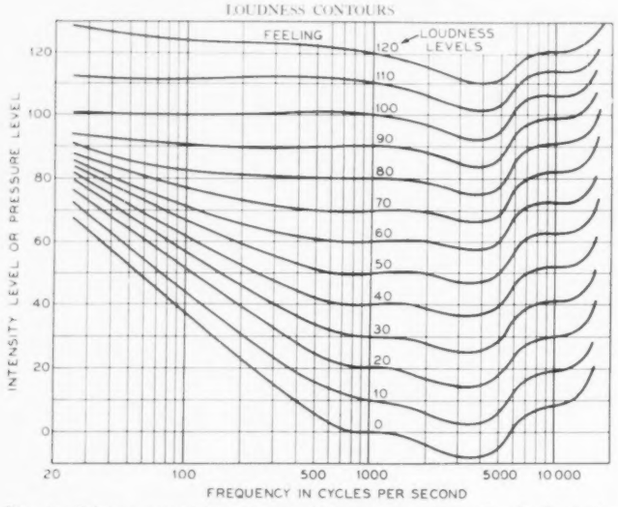

Fig. 1. Relative sensitivity of normal human ear (Am. Standards Ass'n results) to low-, medium- and high-pitched pure tones.

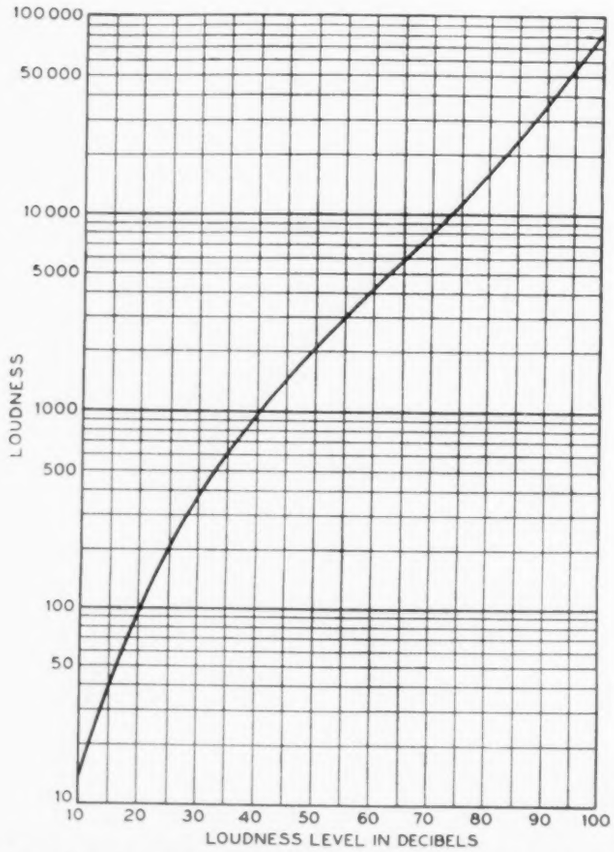

Fig. 2. Relation between loudness (averaged human-ear results) and loudness level (scale of standard instruments).

Weighted sound pressure level is a logarithmic scale expressed in db above 0.0002 bar, at 1000 cycles, of sound pressure, weighted according to an equal loudness contour suitable to the level of the sound measured. The ear is not equally sensitive to all frequencies, and the curves expressing this sensitivity (the *equal-loudness contours*) change for each value of intensity level. Weighted sound pressure level is the result of an attempt to duplicate the action of the ear for complex sounds.

Weighted sound pressure level is the most useful measurement obtainable from complex sounds as an indication of their loudness. Meters can be calibrated to read directly in this scale. This does not express the true loudness of a complex sound, but neither does the observation of an individual listener, for loudness measurements are made on the basis of the average judgment of a large number of observers. When properly used, weighted sound pressure level serves as a loudness scale which agrees quite well with the results of a sound jury. Most commercial sound level meters are designed to read sound pressure level and weighted sound pressure level.

For the purpose of practical noise measurements, and the design of sound or noise meters, there is need for agreement upon the equal-loudness contours for pure tones. Also there is some need for an additional loudness scale based on group judgment as to what constitutes a certain percentage reduction in the loudness of a sound. For both of these magnitudes reliance must necessarily be placed upon experimental data. A number of investigations[4] have been made for the purpose of obtaining such data, and from their results there have been derived relations which can be taken as the best expression of these data, with, however, the necessary recognition that they are tentative, and may need modification as further data are obtained. These relations are expressed in the form of curves published by the American Standards Association.[5] The loudness level of a pure tone propagated as a plane or spherical wave in air, and having a frequency of f cycles and an intensity level of b decibels is defined by the set of curves of Fig. 1. The relation between loudness and loudness level is given by the curve shown in Fig. 2.

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SECTION 3

TOTAL SOUND METERS— SUBJECTIVE INSTRUMENTS.

Most of the present-day studies in acoustics are carried on with the help of instruments of the objective type, exemplified by the common type of total sound meter, or noise meter, or acoustimeter. However, early studies in this field were made on the basis of subjective measurements, and even today much of the work is done in such a way that the ear of the listener is used as the indicating part of the instrument. This may be in the form of a sound jury, in which a number of observers are required to listen to certain sounds or noises, and to compare them on the basis of loudness with standard sounds of adjustable intensity. Or it may be in the form of instruments which are designed to be used in conjunction with the ear, in the measurement of noise level. These subjective instruments are called audiometers.[1]

The Audiometer.

One type of audiometer operates on the principle of the masking of a test tone by the noise. The phenomenon of masking is the effect by which the threshold of hearing for a given tone is raised due to the presence of another tone of different pitch. The equal loudness contours indicated in Fig. 1 are based upon measurements being made in a perfectly quiet room. Any other noise or sound heard in conjunction with the test tone has the effect of raising the lower limit of audibility. In other words, the test tone has to be made louder in order to be heard above the sound of the disturbing tone. In general, tones of lower pitch have more effect on a test tone of given frequency than do tones of higher pitch.[2] The amount by which the threshold of hearing is raised is a measure of the intensity of the noise. This is not arrived at directly, but by calibration. In effect, the listener is subjected to both test tone and noise, and adjusts the intensity of the test tone until it is just barely heard over the noise. This intensity is the new threshold, and the rise over the threshold measured in the absence of all noise, is a function of the intensity of the noise.

One type of audiometer[3] consists of a modified telephone receiver through which the test tone is applied to the ear. The receiver is arranged by means of a special cap, to be held away from the ear sufficiently, to permit the noise to be heard in the same ear. A calibrated attenuator operated by the listener serves to adjust the intensity of the test tone until the threshold of hearing is reached.

The test sound is usually not a simple tone, but is more often a complex sound, such as a buzzer tone, which is rich in harmonics. Such a tone may contain frequency components ranging from 200 to about 3000 cycles per second. Or it may be a phonograph record, or a vacuum-tube oscillator, providing a warble tone oscillating over a fixed range in frequency. The warble tone seems to be the most desirable, especially if it is permitted to vary through several ranges, such as a low-, an intermediate-, and a high-frequency range. The buzzer tone provides the means of making this instrument simple and portable, and for that reason is most often used. In using this instrument, since both sounds are applied to one ear, the other ear must be stopped in order not to affect the balance due to conduction of noise energy from the second ear to the first.

Another type of audiometer described by Churcher[4] employs a pure tone, of intensity up to 110 db, applied through a telephone receiver directly to one ear. The other ear is exposed to the noise. Since it is seldom possible to interrupt the noise to compare it with the test tone, both sounds are presented simultaneously. The reference tone is adjusted by means of an attenuator to be as loud as the noise. The range in frequency of the test tone is generally from 700 to 1000 cycles per second, a value of 800 cycles being found best. After one adjustment is made, the telephone receiver is applied to the other ear and the test repeated.

A vacuum-tube oscillator is used to supply the test tone. The receiver has a tuned diaphragm and is tightly fitted to the ear in order to be capable of supplying high intensities. In general, there is some spread in the settings made by different observers, for a given noise, but the amount of the spread is quite small.

Tuning Fork Audiometer.

Another type of subjective sound meter based on the masking effect of the noise, is the tuning fork audiometer.[5] This instrument requires a tuning fork of known rate of decay and initial amplitude, and a stop watch. The fork is arranged to be struck by mechanical means, with a blow of constant strength. When the amplitude of fork vibration has fallen to a known initial value, the stop watch is started. The fork is held close to the ear, and when the noise to be measured just masks the sound from the fork, the watch is stopped. Since the rate of decay of the fork is logarithmic, it can be expressed in decibels per second. The amount of masking due to the prevailing noise level is obtained by a simple subtraction of the decibel decay while the stop watch is running, from the known initial amplitude in decibels. The determination of the prevailing noise level itself from the amount of masking depends upon the fork calibration and the frequency spectrum of the noise.

In one particular instrument of this type the fork has a frequency of 512 cycles per second, and the rate of decay is 1.81 db per second. This low rate of decay is made possible by a special mounting. The striker is spring-driven with a fixed force. A mark on one prong is used to determine when the fork has attained its known initial amplitude. Because of the persistence of vision, a definite pattern can be chosen which will serve to indicate this amplitude. A magnifying lens is provided to observe this pattern. The initial amplitude is determined from the known rate of decay and the measured time of decay from the appearance of the chosen pattern to the threshold value under quiet conditions. For this fork the initial amplitude is 116 db above the 512-cycle threshold. Since the rate of decay of the fork is constant, the watch dial may be calibrated directly in decibels for a given fork.

Since this type of audiometer makes use of a pure sound as its test tone, its use with certain types of noises is quite unsatisfactory. The masking of one tone by another close to it in frequency is variable, and is dependent upon the actual frequencies. Consequently it is necessary to supply a group of forks, and to make use of those which differ in frequency by a considerable amount from that of the noise. This instrument is extremely small and portable, and with practice, may be used to determine noise levels with considerable accuracy.

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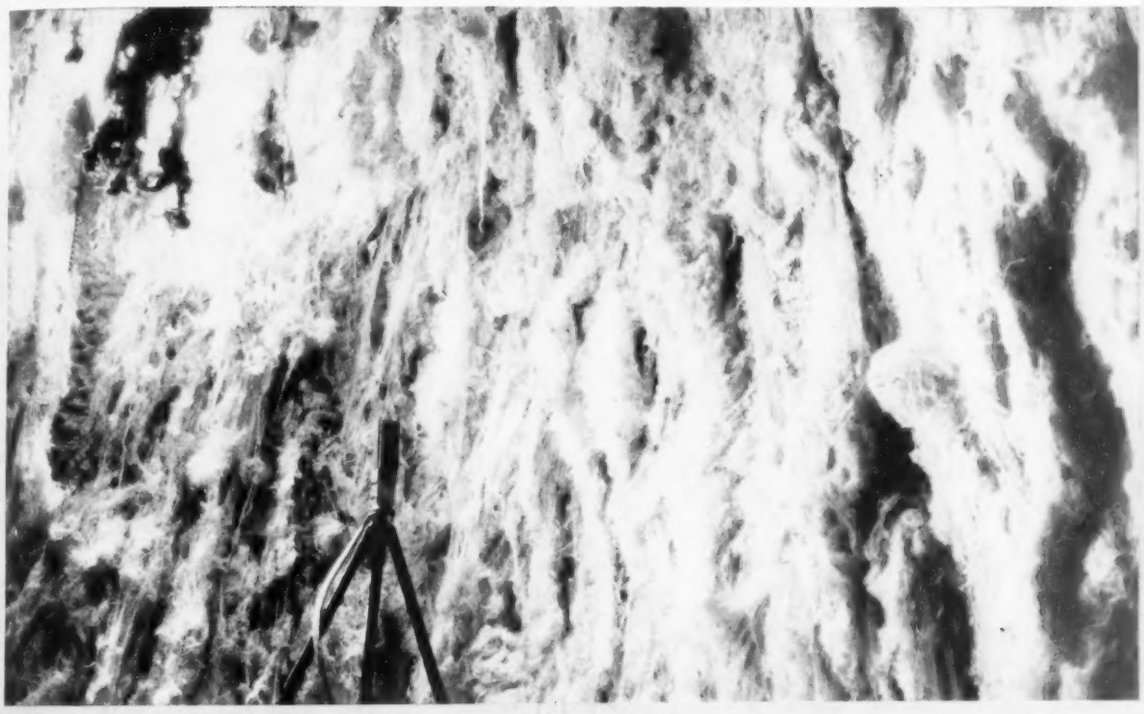
To Measure—SOUND ELECTRICALLY



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SECTION 4
TOTAL SOUND METERS—OBJECTIVE INSTRUMENTS.

Of the many different makes of total sound meters on the market, and in everyday use in the acoustical conditioning of machines and buildings, few differ appreciably from the conventional type. This type consists essentially of the components indicated in Fig. 3. There are five essential parts: (1) a microphone for converting the sound energy into an equivalent electrical voltage; (2) an amplifier for increasing the energy of this signal to the point where it can operate an indicator; (3) an attenuator for adjusting the gain of the amplifier to provide a more or less constant output to the indicator in spite of considerable range of sound intensity applied to the microphone; (4) a weighting network, or control of the frequency response so as to simulate the action of the ear as closely as possible, and (5) an indicating type electrical instrument, the reading of which, in conjunction with the setting of the attenuator, will indicate the intensity level, or pressure level of the sound.

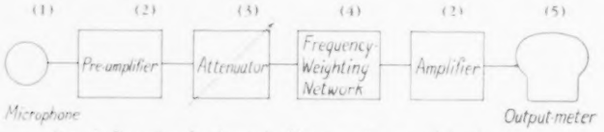

Fig. 3. Functional schematic diagram of a sound level meter.

In these separate components there are considerable variations, and, in general, the value of the instrument, in regard to its accuracy, portability, convenience, and ease and permanence of calibration, lies in the particular design of these several components. Although each individual manufacturer has unlimited freedom in choice of elements, the overall operation of the instrument, and its steady state and transient response, are governed by the standards set up by the American Standards Association.

Microphones.

The microphone[1] is the acoustical element of the sound level meter that translates the sound vibrations into electrical voltages. Corresponding to the sound wave in air, there are periodic variations in pressure, density, temperature, and particle velocity. Any device that measures one or more of these variations may be called a microphone. Although few of the microphones used in sound meters are designed primarily for this application, there are fortunately, a large number of types and designs of microphones used in related sound work that can be adapted for use in noise meters.

The sensitivity of the microphone as a function of frequency, or the frequency response, is an important property of the instrument, just as the frequency response of the entire instrument is important enough to be specified in the standards set up for noise measurements. This response of the microphone is generally determined by calibration.[2] Calibrations are commonly made in terms of either the voltage generated per unit of pressure actually acting on the instrument, or in terms of the voltage per unit of pressure, at the point at which the microphone is situated before the microphone is placed in the sound field. The former is called the pressure calibration, and the latter the free field calibration. Both are important in acoustical work, because unless the microphone is small compared with the wave-length of sound to be measured, the microphone will diffract the sound wave, and the pressure acting on the diaphragm will not be the same as the free field pressure. Diffraction exhibits itself as a directional characteristic of the microphone. In other words, the frequency response varies with the angle of incidence of the waves.

There are, in general, two types of microphones, the pressure microphones, and the velocity microphones, responsive respectively to sound pressure and particle velocity. A microphone for use in noise work must be rugged and stable, and must be capable of holding its calibration for long periods.

Condenser Microphone.

This is the simplest type of microphone, and consists essentially of two parallel insulated plates or diaphragms, one fixed and the other movable under the action of the alternating pressure of the sound wave. Due to the actual configuration of the plates, and their spacing, there is a definite electrical capacitance associated with the assembly. Variation of position of one plate with respect to the other causes a change in this capacitance. Consequently, if a constant potential is maintained across the plates, a current will flow in the circuit, which constitutes the charging current due to the change in capacitance, The potential variation appearing across a series resistance in this circuit is impressed on the grid of the amplifier tube. Some condenser microphones are made with the diaphragm mounted at an intermediate potential, between two grids, between which a fixed potential is maintained. This gives a push-pull action and doubles the sensitivity of the microphone. Because of the high potential required, and the minute currents that flow, the condenser microphone is a high-impedance element, and requires a pre-amplifier at the microphone. This is an inconvenience, although a compensating advantage is had, in that the output can be impressed directly on the grid of the tube without an intermediate transformer.

Dynamic Microphone.

The dynamic type of microphone is the result of an attempt to get away from the high impedance and inconvenience of the condenser microphone. This type is extremely convenient and portable, has greater sensitivity and can be made with equally good frequency response. The construction of the dynamic microphone consists of a circular coil of wire fastened to a thin flexible diaphragm, which is mounted so that the coil is inserted into an intense radial magnetic field concentric with the coil axis. Variations in pressure on the diaphragm cause axial motion of the coil and so generate a voltage which is the output of the microphone. The voltage generated by a coil moving in a magnetic field is proportional to the velocity, and if the output is to be proportional to the sound pressure, the velocity must be proportional to the sound pressure. This means that the impedance of the moving system must be a constant, or it must be resistance-controlled. This condition is provided by proper design of the instrument.

Crystal Microphone.

This type of microphone depends upon the piezoelectric properties of certain crystals, as a result of which, a variation in the pressure applied to the faces of a crystal causes variations in charge to appear on the surfaces of the crystal receiving the pressure. Only certain crystals exhibit this action, two of the most commonly used materials being quartz and Rochelle salt. Rochelle salt has a piezoelectric effect hundreds of times that of most other crystals. It has, however, certain limitations as to mechanical strength, operating temperature and the effect of moisture. These limitations are rapidly being overcome in the newer models, and its light weight, convenience, and moderate sensitivity make it much desired in noise work.

Velocity Microphone.

The velocity type of microphone consists of a loosely stretched strip of metallic ribbon mounted in a magnetic field, so that motion of the ribbon parallel to itself under the action of the variation in air velocity causes a generation of voltage across the terminals of the ribbon. This type has advantages for sound work, particularly because of its directional sensitivity. However, because of size, mechanical limitations, and lower sensitivity it is not extensively used for noise work.

Carbon Button Microphone.

The carbon button microphone has high sensitivity and good mechanical strength but, due to the action of the carbon granules which set up an electrical noise in the circuit, this type of microphone is not used in noise work. However, recent designs of carbon microphones have been improved to the point where they have an extremely low noise level.

Vacuum Tube Amplifier.

The amplifier is that element of the total sound meter that is used to increase the energy of the small signals received by the microphone. Modern amplifiers cover a myriad of types and circuits. Any type of amplifier, whether using transformer or resistance-capacitance coupling, is satisfactory if it has the proper frequency response, gain, stability, and permanence of calibration. The inverse feed-back type of amplifier has been used to good advantage, providing as it does a flat frequency response.

Part of the amplifier is the attenuator, which is usually constructed in logarithmic steps of 5 or 10 db. The minimum step of the attenuator must be less than the range of the indicating instrument. Also included in the amplifier is the frequency response control, or the weighting networks. These may be two or more in number, and are specified by the standards set up by the American Standards association[3] for sound level meters for measurement of noise and other sounds.

The Indicating Instrument.

Most sound level meters use for their indicating instrument a rectifier type a-c. instrument calibrated to read in decibels. The scale range is generally 15 to 20 db. Due to the properties of the decibel scale, and the basic characteristics of the d-c. movement which forms the basis of the instrument, the scale is so uneven that only a relatively small portion of it is open enough to be really useful. Consequently, although the indicator may have a total range of 15 db, the attenuator will usually have a 5 db step, so that the indicator can normally be read in the best part of its scale. The sum of the readings of the attenuator and of the indicator, provides the reading of the entire instrument, which is the sound pressure level at the microphone, above a given base or reference level.

Decibel Meter.

The ordinary d-c. milliammeter is designed to have equal spacing on the scale for equal increments of current. This is secured by having the moving coil, to which the pointer is attached, rotate in an air gap of uniform flux density throughout its range. Since the flux density is constant, the torque on the coil will be proportional to the current, and since the pointer acts against a spring providing a restoring force proportional to the deflection, equal deflections are obtained for equal increments of current.

A characteristic of the decibel scale is that the percentage decrease in current corresponding to one decibel is constant whatever the value of current. But since the actual current change represented by one decibel is smaller for smaller currents, the space on the scale represented by one decibel decreases as the current decreases, or as the decibel loss increases. Consequently the upper portions of the scale are spread wide apart and the lower portions are crowded together.

A decibel meter has been designed to overcome this condition and provide a uniform scale.[4] In this meter, an attempt has been made to decrease the torque on the coil as the current increases, by reducing the flux density in which the coil operates as it rotates toward the position of higher current. This is done by constructing a variable-width air gap. The maximum flux density, or narrowest gap, is found at the position of minimum current, and in clockwise rotation of the coil the gap increases at the proper rate to make the scale divisions uniform. This type of meter has the advantage of a uniform scale, but is inherently of lower sensitivity, since it applies to the whole scale the sensitivity corresponding to the crowded portion of the original scale. Also, at the upper extreme of rotation, due to the lowered flux density, the damping force available is less than in the conventional type of meter.

A commercial instrument that makes use of a uniform scale decibel meter is that described by Ballantine.[5] This is essentially a wide range a-c. vacuum tube voltmeter, having a special d-c. indicator whose deflection is proportional to the logarithm of the current. One advantage of a uniform scale reading in decibels is that the percentage of

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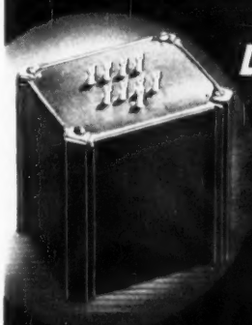

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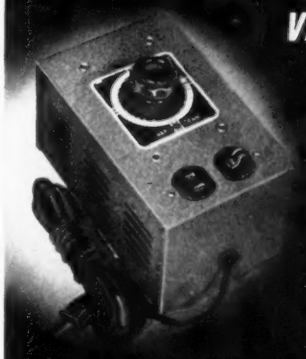

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error in reading is the same at all parts of the scale. It also lends itself well to a multi-range meter, where the several scales can be in the ratio of 10 to 1.

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SECTION 5
STANDARDS FOR SOUND METERS.

The Standards for Sound Level Meters for Measurement of Noise and Other Sounds, prepared by the American Standards Association,[1] have covered the important points to insure that the values of sound level indicated by different meters for a given sound condition will be the same.[2] In particular they have specified:

1. The base or reference intensity, which is given as 10^{-16} watts per square centimeter, at 1000 cycles, in a free progressive wave

2. The rule of combination in the case of complex sounds, which provides that the meter shall indicate the sum of the equivalent 1000-cycle free-wave intensities of the different single-frequency components, or in other words, the power indicated for a complex wave shall be the sum of the powers which would be indicated for each of the single-frequency components of the complex wave acting alone.

3. The frequency response, which is indicated by the two sets of curves given in Fig. 4. If one frequency response only, is available, it shall be that corresponding to curve A. If more than one frequency response is available, either the response shown by curve B, or a flat response, or both, may be used in addition to curve A. Curves A and B correspond to the 40-db and 70 db equal-loudness contours respectively. In other words, the selective circuits whose pass characteristics are indicated by curves A and B are such that they will accentuate those frequencies to which the ear is most sensitive, and diminish those to which the ear is least sensitive, at the respective levels of 40 and 70 db. The tolerances allowed in the response are given by the dashed lines.

4. The dynamic characteristic of the indicating instrument. It is intended in this respect that in transient response the meter shall match the ear, which has a lag on transient sounds, of about 0.2 second. Thus the instrument must indicate full, or steady-state value, on pulses of a 1000-cycle tone, of duration of 0.2 to 0.25 seconds. The action on the sudden application of a 1000-cycle tone indicates that the overswing of the meter must not be greater than 1 db. And the indication of the meter for a 1000-cycle pulse of duration 0.1 second must be at least 1 db less than the steady-state value for that sound intensity. For certain types of sound measurements it may be desirable to have a slow acting indicating instrument which, for steady-state measurements, must indicate the same value as the one specified above.

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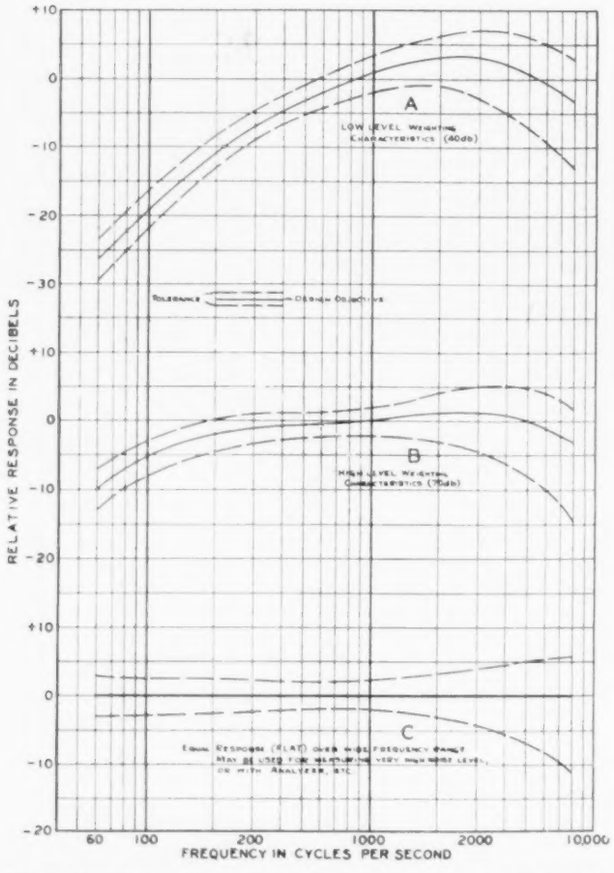

Fig. 4. Overall free field frequency responses and Am. Standards Ass'n tolerances for sound level meters.

Fig. 5. General Radio Company's sound level meter, "Type 759-A."

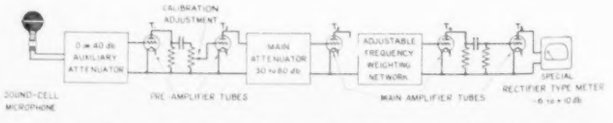
CALIBRATION ADJUSTMENT
0 to 40 db AUXILIARY ATTENUATOR
MAIN ATTENUATOR 30 to 80 db
ADJUSTABLE FREQUENCY WEIGHTING NETWORK
SPECIAL RECTIFIER TYPE METER -6 to +10 db
SOUND-CELL MICROPHONE
PRE-AMPLIFIER TUBES
MAIN AMPLIFIER TUBES

Fig. 6. Functional schematic diagram of Fig. 5 sound level meter.

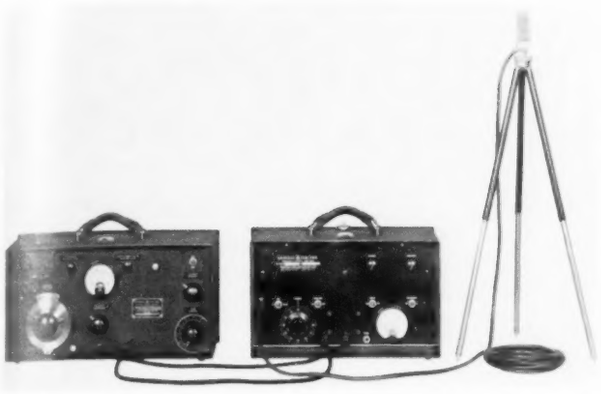

Fig. 7. General Electric Company's sound level meter (center), set up with analyzer unit (left).

NOTE—G-E engineers inform us that a new sound level meter, now in final development, will be released in October 1939, so that the one shown here is considered obsolete.—Ed. *Instruments.*

SECTION 6
COMMERCIAL NOISE METERS

In addition to the essential components which all commercial noise meters provide, some provide one or more additional features which make the instrument more convenient or useful under certain conditions. The Type 759-A sound level meter made by the General Radio Co. is shown in Fig. 5. This is based on the schematic circuit indicated in Fig. 6. It will be seen that an auxiliary attenuator of 40 db is provided with a high gain amplifier, which makes the total range of the instrument from 24 to 130 db. Preamplifier stages are provided between the auxiliary and the step-by-step attenuators, and between the latter and the weighting networks. The main amplifier stages follow the latter, and lead to the rectifier type output meter having a range of 16 db. This instrument has three weighting networks, namely the 40-db network which is used for sound levels between 24 and 60 db, the 70-db level network which is used between 50 and 90 db, and the flat response which is used between 80 and 130 db.

This instrument has a non-directional microphone which may be removed from the instrument and set up at a distance by means of an extension cord and tripod. As with most other similar instruments, vibration-free tube mounts are provided to make the instrument non-microphonic, and the design is such as to make the instrument free of magnetic pickup. This is important, for in many of the places where noise meters are used there is considerable vibration and noise, which must have no effect on the amplifier itself. Calibration of the amplifier is checked by means of a voltage obtainable from a 115-volt 60-cycle a-c source. Connections are provided by means of a socket in the microphone compartment.

Fig. 10. Westinghouse Elec. & Mfg. Co.'s sound level meter. (Also shown is vibration pickup referred to in Section 7).

Fig. 11. Sound level meter, "Type RA-224," of Electrical Research Products Inc.

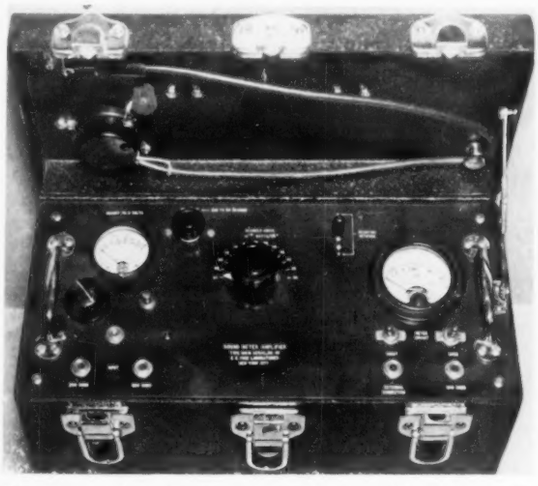

Fig. 8. A sound level meter built by the E. E. Free Laboratories.
NOTE—This shows "manufactured" form, now superseded by equipments built to individual specifications.

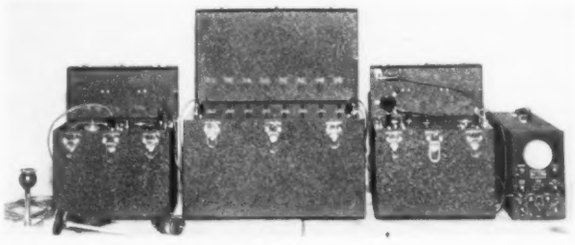

Fig. 9. E. E. Free Laboratories' equipment used in investigation of soundproofing of airplanes: microphone; microphone amplifier; 8-band frequency analyzer; sound level meter; c-r. oscilloscope of standard commercial type.

The sound level meter made by the General Electric Co. is shown in Fig. 7. In this instrument, an overall calibration of microphone and amplifier is provided by means of a mouth blown whistle which provides a tone of about 1000 cycles of a definite intensity. As is the case with all commercial noise meters, external connections are provided from the output of the amplifier so that another indicating meter may be used, or the output may be applied to a frequency analyzer for further study.

Three other types of sound level meters, those made by the E. E. Free Laboratories, the Westinghouse Electric & Mfg. Co. and Electrical Research Products, Inc. are shown in Figs. 8, 9, 10 and 11 respectively.[1]

The electronic a-c. voltmeter manufactured by Ballantine[2] is essentially the same as the electrical-measurement portion of the usual type of sound level meter. It is a voltmeter of high sensitivity and wide range, and has a flat response for both audio and supersonic frequencies. A dynamic microphone which is available, is all that is necessary to convert it into a sound level meter. The weighting network is in a separate unit, and the decibel scale output meter and attenuator are provided in the instrument.

The rectifier type output meter is novel. It is a special d-c. type, in which the deflection is proportional to the logarithm of the current. In addition, a feedback circuit is provided whereby some of the rectified current is brought back to the input circuit of the amplifier. By feeding back energy of reversed phase to the input of the system, the rectifier characteristic can be straightened out and the distortion normally present considerably reduced. This use of feedback has the effect of providing a rectifier characteristic that is essentially similar to that of an ideal rectifier. Thus the output current can be made rigidly proportional to the a-c. voltage applied to the input terminals of the amplifier.

In most rectifier circuits high series resistance is used to overcome the non-linearity of the rectifier characteristic. This has the effect of making the output current proportional to the peak of the a-c. input voltage. The use of an ideal rectifier and small series resistance makes the output current proportional to the average value of input voltage. Thus the effects of harmonics (which are mainly evident in the peak values) are reduced, and the readings of the output meter are more nearly an indication of the true r.m.s. value of the fundamental.

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SECTION 7
VIBRATION MEASUREMENT

In studying the overall sound in a room, the total sound reaching the microphone is of interest. However, when the noise produced by a given machine is of interest, it is necessary to separate the noise of this machine from the background noise. Of course, if the machine is portable, it may be moved into an acoustically treated room in which the background noise level is sufficiently low so as not to be of importance in the measurement of sound level. If the machine is not portable, it becomes necessary to separate the noise of that one machine from the background noise. In such a case it may be of help to study the vibration conditions of the machine, inasmuch as the noise radiated comes from vibrating surfaces. Measurements of the amplitudes of vibration and the frequencies of the various parts of the machine will give a useful answer. Consequently it is common practice to use a microphone and vibration pickup interchangeably on the input of the amplifier.

Manufacturers of sound level meters provide vibration pickups to be used with their instruments.[1] These pickups are of several types:[2] the piezoelectric, magnetostrictive, magnetic dynamic, and the magnetic reluctance types. Several types of vibration pickups are indicated in Figs. 10, 12, and 13.

Vibration pickups are simple oscillating systems, arranged to be driven directly by contact with the vibrating member, or to be driven by reaction, as in the seismometer type of pickup. Among the crystal type pickups there is the direct-driven or displacement type, in which the voltage output is proportional to the displacement of the vibrating member, and the reaction type, in which the crystal is mounted in such a manner that only one portion is fastened to the case (which is driven by the vibrating member). As the case vibrates, the crystal is deflected due to its own inertia, and produces a voltage proportional to the acceleration of the case.

In the magnetic type, the voltage generation is the result of the movement of a coil in a magnetic field. One construction is similar to that of the dynamic type of loud

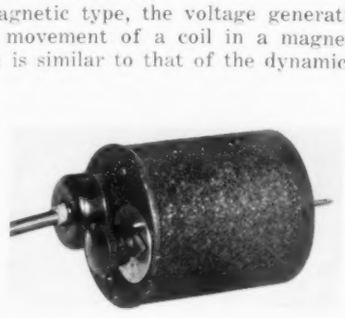

Fig. 12. General Electric Company's electromagnetic type vibration pickup. (Ref.: Muchow, A New Sound Level Meter, *G-E Review*, June 1936.)

speaker in which a circular coil moves in a radial magnetic field. Another construction provides for the voltage to be induced into a coil wound about a fixed armature while a spring-mounted magnet is vibrated in a manner to vary the flux threading the armature. Inasmuch as the voltage generated by a coil moving in a magnetic field is proportional to its velocity, this type of pickup will indicate the velocity of vibration of the surface. This voltage can be differentiated or integrated by appropriate circuits to provide a voltage which is proportional to the acceleration or the displacement respectively. A series resistance-capaci-

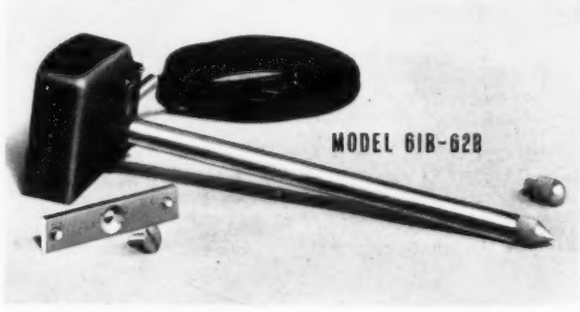

Fig. 13. Shure Brothers' piezoelectric type vibration pickup.

tance circuit connected across the output of the pickup, with the amplifier connected across the resistance, will provide differentiation; while if the amplifier is connected across the condenser, the circuit will provide integration. Of course in each case certain numerical relations must exist between the circuit constants.

For frequency analysis, it is immaterial what type of pickup is used. However, for magnitude studies, it is to be noted that the displacement type of pickup will give a voltage independent of frequency, depending only upon the amplitude of vibration. For constant amplitude of vibration, the velocity type will give a voltage that increases proportionately with the frequency, while the acceleration type gives a voltage which increases as the square of the frequency.

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SECTION 8

...TAL SOUND METERS—RECORDING TYPES

Any of the individual types of sound level meters may be adapted to be indicating or recording, or both. In general they are used for different purposes, the recording types being extremely useful in the study of transient noise effects. Several examples of the automatic recording type of total sound meters have been described in the literature, the most notable example being the High-speed Level Recorder described by Wente, Bedell, and Swartzel.[1] This instrument consists of the usual type of sound level meter arranged with a servo-mechanism to control the position of the attenuator so as to keep the output always constant. In the ordinary indicating type of meter, a range of some 10 to 15 db is permitted in the indication and the finest step in the attenuator is 10 or possibly 5 db. If the number of positions of the attenuator were increased, and the difference in decibels between successive positions made sufficiently small, the position of the attenuator could be adjusted to hold the meter reading constant at all times. The position of the attenuator would then be an indication of the sound level.

This is accomplished in the instrument by means of an attenuator covering 60 db in 1-db steps, motor-driven by means of two clutches in such a manner that by engaging

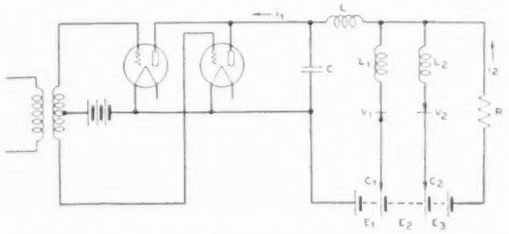

Fig. 14. Simplified rectifier and control circuit diagram of sound level recorder described by Wente, Bedell and Swartzel.
(Courtesy *Journal Acoustical Society of America*)

one or the other of the two clutches, the attenuator shaft can be driven in either direction. These two clutches are controlled by the current flowing in a rectifier circuit connected to the output of the sound level amplifier. The circuit for doing this is shown in Fig. 14, where L_1 and L_2 are the two clutch coils. L_1 operates the attenuator in such a direction to decrease the output of the amplifier, and L_2 operates to increase the output. If the two rectifiers V_1 and V_2 are considered for zero voltage drop, the maximum current that can flow in R, that is, the maximum value of i_2, is equal to $(E_2 + E_3)/R$. If the current taken by the two vacuum tubes is greater than this, the additional current must flow, under the influence of the battery E_1, through V_1 and L_1 operating the clutch to reduce the current. If the current is less than this value no current will flow in L_1, and no current will flow in L_2 until the total current becomes less than the value of E_3/R. Thus for currents less than one given value, one clutch operates, and for currents greater than a second given value the other clutch operates. By proper design these limits can be brought as close together as desired, the difference preferably being less than that necessary to cause the change of the attenuator by its smallest division.

At the same time that the attenuator is changed, its position is indicated on a roll of waxed colored paper by means of a stylus which scrapes off the wax and bares the colored paper underneath. This is the transient record of the sound level recorded by the instrument. By choice of attenuator steps and gearing, several ranges of speed of response are provided for the instrument.

In addition to its use in the direct measurement of noise or sound level, this instrument finds considerable application in the study of speech and music,[2] of architectural acoustics[3] and of the absorption and transmission of sound through various types of materials[4].

A similar type of instrument is that supplied by the Sound Apparatus Company.[5] It consists essentially of an input potentiometer, amplifier, and rectifier, and a servo-mechanism to control the position of the potentiometer in

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order to compensate for changes in input signal, and so keep the output of the rectifier as nearly constant as possible. The output of the rectifier, through the medium of a small motor and magnetic clutch, serves to control the position of an arm upon which is mounted the recording stylus and the potentiometer contact. The stylus records its position on a roll of waxed paper which is driven at constant speed by means of a small synchronous motor. Three different speeds of paper drive are provided.

Fig. 15 is a schematic circuit of the instrument. A portion of the input signal (determined by the position of the potentiometer) is applied to the amplifier, and thence to the

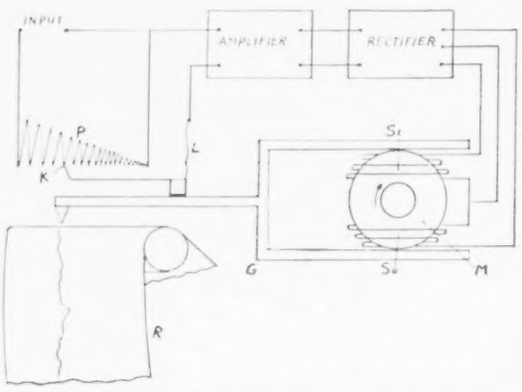

Fig. 15. Simplified diagram of Sound Apparatus Co.'s sound level recorder.

balanced rectifier. The latter consists of two parts, one, supplying a constant small d.c. obtained from a 60-cycle source, and a second part, consisting of the rectified output of the amplifier. These two voltages are applied to two opposing coils wound about a rotating steel disk. Two prongs of a magnetic fork slide on the edges of the disk, with enough clearance between them so that only one prong can be in intimate contact with the disk at a time. This fork carries the potentiometer contact and the stylus.

Operation is as follows: With no signal, the output of the first part of the rectifier attracts to the disk the proper prong of the fork to drive it toward the zero position. In this position, the potentiometer setting is maximal. As a signal appears across the input of the system, the rectified output of the amplifier is applied to the second operating coil, and serves to counterbalance the pull of the first coil, and the friction of the fork prong on the disk is reduced. If the signal is great enough, the opposite prong of the fork is attracted to the disk, and the friction causes the fork to be driven away from the zero position. However, this reduces the setting of the potentiometer, which reduces the output of the rectifier, and as soon as the two currents are balanced, the fork stops. Further increase in signal drives it out farther and so lowers the setting of the potentiometer, while a decrease in signal drives the fork back toward the zero position. The minimum change in input signal to cause the fork to move is 0.004 volts.

Several different interchangeable potentiometers are available, and can be quickly placed in the instrument. These cover ranges of from 25 to 75 db in 100 steps, which makes the minimum step available about 1/4 db. The response is flat within 0.4 db from 30 to 15,000 cycles. These potentiometers, calibrated in decibels, are used for electrical measurements. For sound measurements, a potentiometer calibrated in phons* is used. This has its associated weighting network, and has a range from 30 to 105 phons. In the frequency range of 30 to 10,000 cycles this system agrees within 2 phons with the standard weighting curves. The speed of operation of the stylus depends upon the speed of the motor and the size of the disk. For normal operation the complete range is covered in 0.132 second, providing a speed of 560 db per second.

*The phon is a unit of loudness level. See Appendix on the Decibel Unit.

Another type of recorder accomplishes the same results in a slightly different manner. In this instrument, described by Ballantine,[5] the gain setting of the attenuator is fixed, and the gain of the amplifier is varied by changing the grid bias. The output reading of the amplifier is indicated by means of a galvanometer which, with a source of light and a photosensitive paper, provides a record of the sound level at the microphone.

The instrument, as described, was designed for taking overall frequency characteristics of acoustical equipment. It comprises in the generation circuit a beat frequency oscillator, amplifier, and loudspeaker; and in the recorder circuit a microphone, amplifier, logarithmic voltmeter and galvanometer. This gives a photographic record, in which the abscissa are controlled by the position of the condenser in the oscillator, and the ordinates are the voltmeter readings in decibels. The recording unit could just as easily be used to measure intensity level irrespective of what caused the sound.

The logarithmic voltmeter[6] is the important part of the recorder. This amplifier makes use of two type 551E tubes in which the gain of the tube is an exponential function of the grid bias.† In operation, the output of the amplifier is

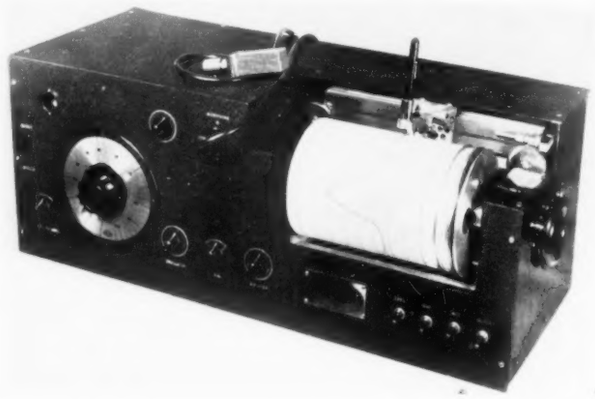

Fig. 16. Audio-frequency response recorder of Tobe Deutschmann Corp.'s Instrument Division.

rectified, filtered, and then applied, as a bias, to the two remote cut-off tubes. The larger the output, the less the gain of the tubes, which act as regulators to maintain constant output, as do the automatic volume control tubes in modern radio sets. The value of bias impressed on the tubes is approximately a logarithmic measure of the signal input to the amplifier, and is indicated by means of a galvanometer. Phase connections and time constants throughout the amplifier are important, and it is particularly important to reduce the time constant of the output filter if rapidly changing sound levels are to be measured.

Another type of amplifier for logarithmic recording is described by Taylor.[7] In this amplifier use is made of the logarithmic characteristic tube of the 6D6 type. However, because the characteristic is not entirely logarithmic, an attempt is made to compensate for this difference by means of the addition of other tubes in parallel. In this way the combined characteristic can be made truly logarithmic. In actual use, in addition to the primary 6D6, a second 6D6 is used with greater bias, and two 6C6 tubes in parallel. The resulting curve of plate current *vs.* input signal can be made closely logarithmic.

Another instrument useful as a recording sound level meter, although designed primarily for recording the audio-frequency response of acoustic instruments and sound systems, is the Audi-o-Graph (Fig. 16) of the Tobe Deutschmann Corporation's Instrument Division, Canton, Mass. This comprises (1) a beat frequency oscillator delivering a continuously-variable audio frequency voltage for application

†Since the date of publication of this paper, other tubes of this type have been put on the market which may serve this purpose even better.

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- A multi-stage stabilized feedback amplifier having over 30 db feedback, which allows high output at low frequencies with low distortion and a flat response.
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directly to the system under test, (2) a calibrated standard crystal microphone for picking up sound waves when the instrument is used as a recording sound meter, (3) a suitable audio-frequency amplifier to insure ample voltage for operating the recorder, (4) a motor-actuated pen responding to changes in audio-frequency voltage, and (5) a chart holder and charts graduated in decibels.

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SECTION 9
SOUND ANALYSIS INSTRUMENTS

General Wave Analysis.

Among the various types of electrical instruments that have been borrowed for use in the field of acoustics, the most important, except for the vacuum-tube amplifier, is the wave analyzer. This is an instrument for the separation of the harmonic components of a complex electrical wave. Its use in acoustics is in the determination of the harmonic content of complex sounds.

The use of an harmonic analyzer in acoustics is not new. Two of the earliest great investigators in this field, Helmholtz and Rayleigh, made use of acoustical resonators which served to identify components to which the resonators were tuned, and to give a rough idea of their magnitudes. Helmholtz' work with these resonaters was so extensive that his name has since been given to a particular type of acoustical resonator.

A complex periodic wave can be considered as the sum of a number of pure sine waves of various amplitudes and frequencies, and the problem of wave analysis is concerned with the determination of these amplitudes and frequencies. One possible way to analyze an unknown wave is to record it on film and analyze the resulting curve graphically or mechanically for its components.[1] If a resonator is exposed to this complex wave (whether in the form of acoustical resonators applied to the original sound, or to electrical resonators applied to the electrical output of the microphone amplifier), and if there is a component in the complex wave of the same frequency as that to which the resonator is tuned, the resonator will be set into oscillation, and by the amplitude of oscillation will indicate the magnitude of the particular harmonic component. Of course, any resonator will respond to frequencies over a finite range, and will act as a band pass filter of more or less considerable width. The wider the band the less accurate is the mechanism for separating components which are close together in frequency. That is the reason why

acoustical resonance is seldom made use of at the present time for sound analysis. Nor is electrical resonance sufficiently sharp for the purpose of most acoustical analysis.

It is evident that an analyzer with extremely sharp selectivity is of value only when the source of voltage, or of sound, is unvarying. When the instrument is used to analyze the noise of a motor, for instance, or other source where the frequency is subject to slight variation, an analyzer of wider band selectivity is desired. Some instruments provide both a narrow sharp band pass, and a much wider band in order to be useful under different conditions. There are many times when a wide band pass filter is useful, and groups of these are often combined in one instrument to cover the whole audio frequency range in discrete bands[2].

The sharpness of resonance of an oscillating system depends upon the ratio of reactance to resistance, or more accurately, the ratio of energy storage to energy dissipation. This is commonly expressed in the form of the "*Q* number." For a given reactance, the less the resistance the sharper the resonance. With electrical apparatus, that is, with coils wound in the best possible manner on low loss iron, the value of *Q* is in the neighborhood of 200 or less, while with other types of resonance, such as mechanical resonance, values of *Q* as high as several thousand are possible.

Expressing the sharpness of tuning as the width of a band in cycles (at a given value of attenuation from the peak) as a percentage of the mid-frequency, it is seen that it is possible to increase the sharpness of tuning by increasing the frequency of resonance. However, in acoustical problems, the essential factor is the actual width of the band in cycles, and not the percentage width. Consequently it is even less advantageous to choose a particularly high value of resonance frequency. The actual value is made just high enough to avoid difficulty in design or construction.

Early models of electric wave analyzers, and some that are in use today made use of tuned electrical circuits[3] using as many as two or three stages in series. However, the modern types of wave analyzers, in order to obtain sharpness of tuning, make use of mechanical or electromechanical resonators. This group includes the purely mechanical, the magnetostrictive, and the piezoelectric resonators or filters.

The frequency range and the ease of tuning of the resonator are important. An acoustical resonator can be tuned directly to audio frequencies. Some mechanical and electrical resonators can be tuned directly to this range as well. For those resonators which can be tuned over the audio-frequency range, it is only necessary to apply the acoustical wave, or the electrical wave derived from it, to the resonator, and by varying the resonance frequency throughout the desired range, to note the amplitude of response at each setting.

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SECTION 10

DIRECT RESONATING INSTRUMENTS

The simplest example of the direct resonating type of analyzer is that described by Wegel and Moore[1]. This instrument has two ranges, from 20-1250 cycles, and 80-5000 cycles. The complex wave is introduced into a selective network containing a sharply tuned circuit whose frequency of tuning is controlled by varying a capacitance. A maximum response of the network occurs when the frequency to which the resonant circuit is tuned coincides with the frequency of a component of the complex wave. The instrument may be made indicating or recording, or may be used with a telephone receiver as the indicating instrument. The frequencies of the various components need not be harmonics of any given frequency, but may be any frequency whatever within the range of the selective network.

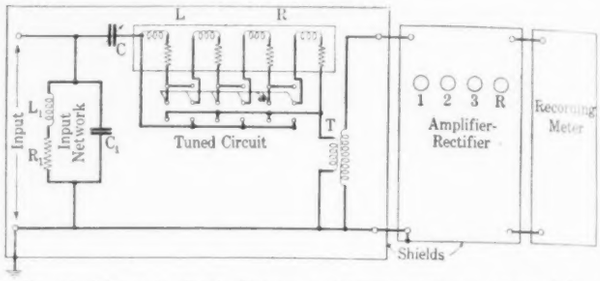

Fig. 17. Schematic circuit diagram of frequency analyzer described by Wegel and Moore.[1]
(Courtesy American Institute of Electrical Engineers)

The circuit is indicated schematically in Fig. 17. As will readily be seen, it accomplishes the analysis by selective shunting of current through the tuned circuit from the input network.

The analyzer described by Delsasso[2] has the direct-resonating type of mechanical filter. It makes use of a sharply resonant mechanical oscillating system that is coupled electrostatically to the amplifier. The amplitude of oscillation is observed optically. The instrument is capable of being tuned directly to the frequencies of the various components of the complex sound to be analyzed.

The resonant system is a small aluminum needle bearing a concave mirror and supported by three fine tungsten wires. The tension in the system is regulated by a micrometer screw through an elliptical spring. The angular separation of the wires can be adjusted by a second micrometer. The mirror, needle and wires constitute a sharply resonant mechanical system, the natural frequency of which is determined by the moment of inertia of the needle and mirror, and the restoring torque supplied by the suspensions. The natural frequency is a direct function of the wire tension and can be determined from the reading of a single micrometer. The range of frequency is from 20 to 550 cycles per second.

The driving force is obtained electrostatically. The needle is suspended at an intermediate potential, between two charged plates, and by varying the potential of the needle in accordance with the voltage output of the microphone amplifier, the needle is set into oscillation. The mirror on the oscillating system reflects the light from a source to a screen, indicating the amplitude of oscillation by the length of the line of light. Thus, by continuously varying the setting of the micrometer and noting the amplitudes of oscillation, the frequency spectrum of the unknown sound can be determined. This instrument is portable and extremely simple. It obviates the need of additional oscillator and modulator, used with heterodyne types of analyzers.

Another type of mechanical resonating analyzer is described by Hickman[3]. In this instrument a large number of separate resonators, consisting of small tuned reeds, are set into vibration electromagnetically. They are tuned to definite frequency intervals, and are set into vibration by the current output of the amplifier. Small mirrors on each element reflect the light from a narrow beam to a screen. With the instrument unexcited the screen presents a series of dots of light lying on a straight line. When a current is passed through the exciting coils, those elements which are excited by appropriate components in the current vibrate and their spots of light are spread out into lines of light of different length, set perpendicular to the line of spots. Thus at a glance the frequency and magnitude of each component of the wave can be recognized. This is called the spectrometer type of analyzer.

Modifications of the spectrometer type of instrument have been used in the study of particular sounds in which

certain frequencies are normally present[1]. This is often the case in the study of the noise of rotating machinery. Here certain frequency components are always present depending upon the speed, gear pitch, and other factors of the design. In the study of such a machine for the purpose of eliminating the noise, or in the factory inspection of the machines, tuned reeds of the above type may be built and tuned to the particular frequencies of interest. These are driven by mechanical contact with the frame of the machine. They may be arranged to indicate optically, or electro-magnetically through a vacuum tube amplifier, the amplitude of that particular frequency component in the vibration of the machine.

Another type of direct resonating sound meter is the group filter type exemplified by the Industrial Noise Analyzer developed by Electrical Research Products Inc. of New York[5]. This type is extremely useful where a rapid test instrument is needed, or where the source of sound is of varying frequency and a sharply tuned filter system

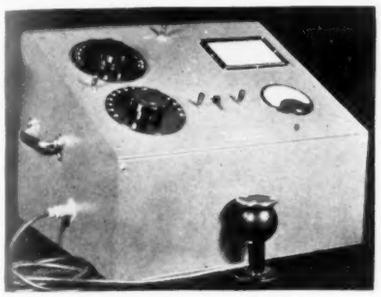

Fig. 18. Industrial noise analyzer, "Type RA-248," of Electrical Research Products Inc., intended for routine acoustic production testing by semi-skilled labor.

would be unsuitable. This instrument (see Fig. 18) is intended primarily for routine acoustic production testing of products in which the noise produced must be limited, or products in which noise or vibration may be used as a measure of quality in assembly. It consists essentially of (1) a microphone which converts the noise produced by the product under test into a corresponding electrical voltage, (2) the electrical wave filters which pass from the microphone to the amplifier only the particular band of frequencies which is affected when a faulty product is tested, and (3) the amplifier and indicator which produce a visible indication of the power level in the band selected. The filter element of the instrument provides for a wide choice of frequency bands and high- or low-pass sections. This is accomplished by using a small number of tapped inductances and capacitor groups which are connected as required for each band by a special selector switch.

Direct resonance methods have the advantage of speed when measuring a single component, but their ability to resolve components not far separated in the frequency spectrum is limited and the adjustments necessary to analyze a large frequency range make their operation slow. Analyzers using heterodyne methods can be built with much higher resolving power and greater ease of adjustment.

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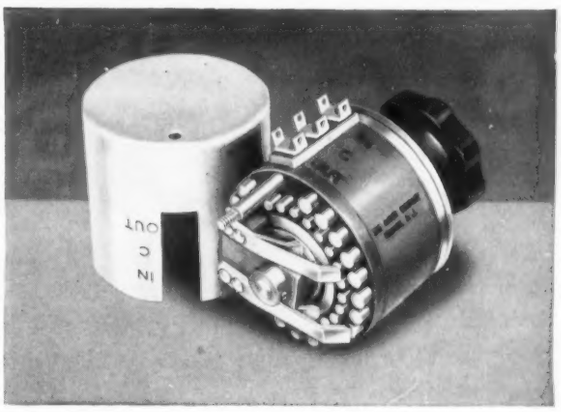

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SECTION 11

HETERODYNE TYPE OF ANALYZING INSTRUMENT

The difficulty with the direct-resonating type of analyzing instrument is the problem of obtaining an adjustable filter or frequency-sensitive element that is selective enough, and still adjustable over the complete audio-frequency range. This is difficult for two reasons: the filters which are inherently the most selective are generally of supersonic or low radio frequency. And secondly, the selective types are not easily adjustable in frequency, for their natural frequency is set by their physical dimensions. Thus, the mechanical resonators of the highest Q values* are the magnetostrictive and piezoelectric oscillators and are naturally of high frequency. When the natural frequency of the resonating element is outside the audio-frequency range, the unknown wave must be converted to the range of the oscillator by modulation of a high-frequency carrier. Most modern analyzers therefore have, in addition to the conventional microphone and amplifier, a carrier-frequency resonator, whose output is combined with that of the wave amplifier and applied to a modulator. These instruments are called heterodyne analyzers.

When voltages of two different frequencies are supplied to the modulator, the result of the modulation is the formation of the sum and difference frequencies.[1] These are the so-called side bands, and each contains the complete frequency spectrum of the unknown wave upward and downward from the frequency of the carrier. The spectrum of the unknown wave is in effect shifted to a new range.

The use of the heterodyne principle makes possible a considerable simplification in equipment. In the simpler types of response analyzers the resonant element has to be successively tuned to all frequencies in the range of the instrument. This makes for a complicated type of filter. However, in the heterodyne type of analyzer a filter of fixed pass frequency can be built and the wave spectrum shifted success-

*The Q value of a tuned system involves the ratio of the energy storage to the energy losses. The higher the Q, the sharper the tuning.

sively by changing the carrier frequency, so that the sum of the unknown component and the carrier are always equal to the resonant frequency of the filter. It is only necessary to shift the frequency of the carrier oscillator through the range of the audio spectrum to obtain the complete analysis of the wave.

In the theory of the thermionic vacuum tube it is well known that the plate current of the tube (for a constant plate voltage) is dependent upon the value of the grid potential. The curve that depicts this relation is the *grid characteristic* of the tube; and the suitability of the tube for any of its various uses depends upon this curve. For use as an amplifier, this curve must be a straight line, so that variations in grid potential are accurately imaged in the plate current. For modulation or detection, the characteristic must be a curve, and preferably a parabola. The plate current of the vacuum tube is then expressible as a power series in terms of the grid voltage. If two harmonic voltages are

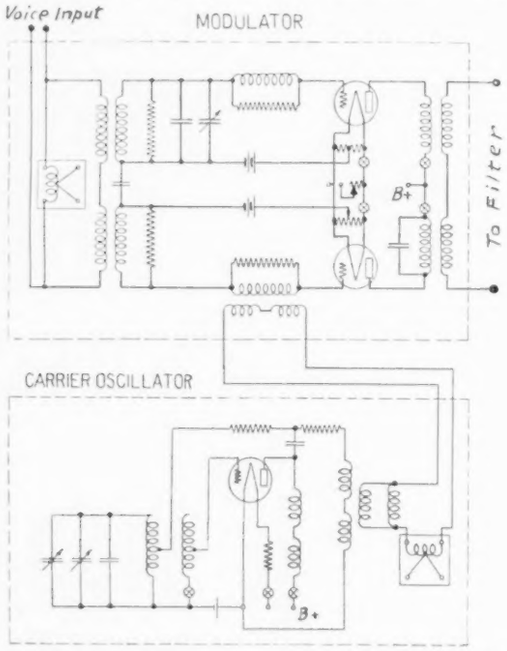

Fig. 19. Portion of analyzer circuit described by Moore and Curtis[2]. (Courtesy *Bell System Technical Journal*. Reproduced with modifications by ed. staff of *Instruments*.)

impressed on the grid (the audio frequency voltage and the carrier), the plate current can be shown[2] by means of the power series expression, to consist of a number of terms involving these two frequencies, and their sum and difference. By suitable design of the modulator the carrier frequency can be eliminated from the output, and since the audio frequency is obviously out of range of the filter, the only remaining components are the sum and difference terms of the side bands. One or the other side band can be eliminated by controlling the range of the carrier oscillator with respect to the frequency of the filter. Most of the modulators as used in wave analyzers are of this type.

The circuit generally used is that of the balanced modulator, an excellent example of which is described by Moore and Curtis.[2] The modulator used employs two vacuum tubes and its circuit is arranged to suppress the carrier frequency together with certain higher order modulation components in the modulator output.

The presence of higher-order components is due to the variation from a square law of the tube characteristic, and can be reduced to any desired extent by keeping the magnitude of the wave to be analyzed as low as is consistent with securing satisfactory meter readings. Suppression of the carrier is desirable for it then becomes possible to carry the analysis to very low frequencies. In analyzing low-frequency components, the frequency of the carrier is close to the inner limit of both sidebands and the relatively large carrier, if present in the modulator output, would tend to obscure the presence of low-frequency components.

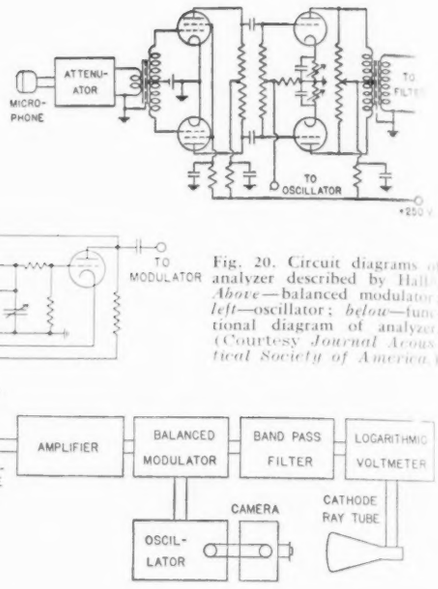

Fig. 20. Circuit diagrams of analyzer described by Hall[5]. *Above*—balanced modulator; *left*—oscillator; *below*—functional diagram of analyzer. (Courtesy *Journal Acoustical Society of America*.)

The circuit of the balanced modulator is shown in Fig. 19. In the grid circuit of each of two tubes the carrier frequency and unknown audio frequency wave are impressed in series. The two voltages are additive in one grid, and subtractive in the other. In the output circuit the transformers in each plate circuit are connected in series opposing. Thus the voltages that are in-phase on the two grids (the carrier) are opposed and eliminated in the output, and only the side bands (and of course the audio frequency) get through. The output then goes to the filter in which the audio-frequency components and the extra side band are removed. In this type of circuit careful attention must be paid to the balancing, both in the tubes and in the circuits, in order to get complete elimination of the carrier.

A similar type of modulator is described by Landeen[3], although his circuit employs a tuned circuit filter. The circuit described by Osbon and Oplinger[4] is similar also, except that provision is made for more accurately balancing out the carrier in the two tubes by adjustment of the actual carrier voltage impressed on the grids of the two tubes. In the circuit described by Hall[5] shown in Fig. 20, balance of the two opposing sections of the circuit in order to eliminate the carrier, is accomplished first, by selection of the triodes used, and second, by adjustment of grid bias on one modulator tube, and by adjustment of the point of application of plate voltage on the output resistance across the primary of the output transformer.

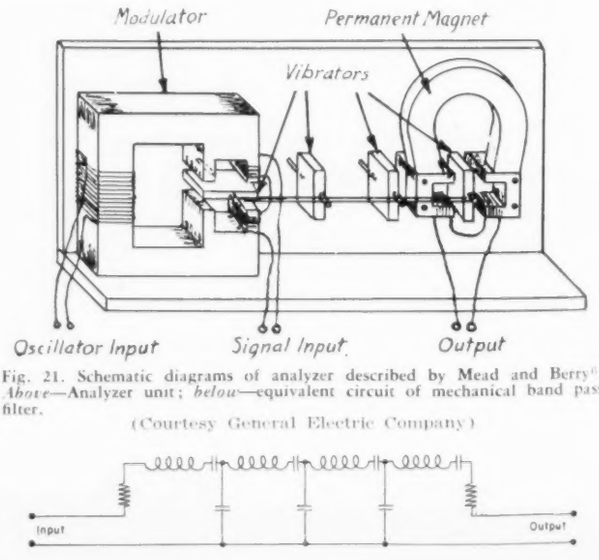

Fig. 21. Schematic diagrams of analyzer described by Mead and Berry[6]. *Above*—Analyzer unit; *below*—equivalent circuit of mechanical band pass filter.

(Courtesy General Electric Company)

A novel type of modulator is utilized in the instrument described by Mead and Berry.[6] The modulation is accomplished in a magnetic circuit which leads directly into a three-stage mechanical filter. The carrier and audio-frequency currents are each applied to coils surrounding portions of a laminated magnetic structure in the air gap of which is pivoted a small armature. The construction is such that either current alone exerts no force on the armature, but when both are present, the sum and difference frequencies are set up in the flux in such a manner that the armature can respond. The system is shown schematically in Fig. 21. Due to the carrier current, an oscillating flux is set up in the main magnetic circuit, which flux (if the amplifier current is zero) divides equally between the two pole tips and crosses the air gap at right angles to the small armature set in a balanced position in the gap. Similarly, with the amplifier current applied alone and with amplifier coils magnetically reversed, fluxes are set up in the local pole tip circuits, which make use of the armature as part of their circuit. However, since they are opposed in direction through the armature, and if they are balanced, there will be no flux in the armature, and therefore no tendency for it to move. Consequently in the case of either current alone there is no action. If both currents are applied, flux passing down through one pole tip is forced through the armature into the lower pole tip on the other side of the axis. Hence there is a tendency for the armature to turn, and it will be pulled in one direction as long as both currents maintain their original directions. As soon as one or the other of the two currents reverses, the torque on the armature is reversed, and it is pulled toward the other pole tips. The armature will respond in such a way as to include in its complex motion, components of frequency equal to the two applied frequencies, and their sum and difference frequencies.

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SECTION 12

FILTERS FOR HETERODYNE INSTRUMENTS.

While most types of heterodyne analyzers make use of the same or similar modulator circuits, they differ radically in the design of their filter systems. The simplest type, of course, is the electrical filter network. As pointed out previously, this is not capable of the sharpness of tuning that can be had in mechanical filters, but in the early types of analyzing instruments, extensive use was made of this type of selective network.

Even using the selectivity of an electrical filter, it is better to use the heterodyne type of analyzer, for in that case the frequency to which the filter is tuned is fixed, and it can be made up of a number of tuned stages in series, thereby providing a much higher value of Q. In the circuit described by Landeen[1] a section of tuned circuit was followed by two stages of amplification and two further stages of tuned circuit. The natural frequency of the tuned elements was 800 cycles. Because of the particular frequency of filter as chosen, it was extremely important to have a perfectly balanced modulator, which was of the type illustrated in Fig. 19.

An electrical tuned circuit filter is also described by Schuck.[2] However, his circuit makes use of a chain of tuned circuits with loose coupling between successive sections. This gives a narrow sharp response curve. The width of the pass band depends upon the resistance in each circuit and the amount of coupling. With practical materials obtainable, the maximum resolving power is still well below that obtainable with mechanical filters. This type of circuit involves also a considerable loss in power.

A good example of the mechanical type of filter is that described by Osbon and Oplinger[3] and shown in Figure 22. Here the resonant element is a brass rod supported at its center and excited so as to vibrate longitudinally. The natural frequency of this oscillator is that for which the wavelength is equal to twice the length of the rod. A vibrational node appears at the center (where the rod is supported) and antinodes at either end. If the rod is driven at one end at its natural frequency, it resonates and a pickup coil on the other end will provide a voltage which is a function of the amplitude of vibration. The driving and pickup coils are similar to each other, and to the driving coils of a dynamic loud speaker; *i.e.*, cylindrical coils moving in a radial magnetic field. The amplifier output is connected to one coil, and the output meter to the other. The central support is a flexible diaphragm which permits a slight unbalance in the two halves of the rod, which seeks its own nodal point. The diaphragm, mounted in rubber, is stiff enough so that its amplitude of motion is limited to a small value. The selec-

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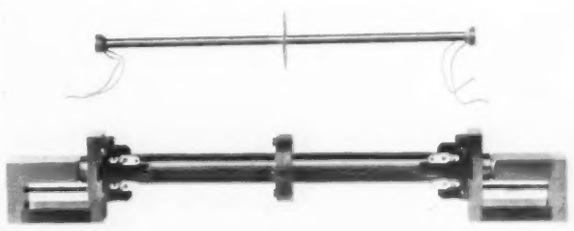

Fig. 22. Westinghouse Elec. & Mfg. Co.'s mechanical filter. *Above*—filter unit; *below*—assembly.

tivity is found to be a function of the diameter of the rod, larger rods providing sharper response. However, for noise measurement, due to the lack of extreme constancy of the tones to be measured, a system of too sharp a selectivity is not warranted. The rod used is 0.25″ in diameter. In the output circuit, the coupling transformer is tuned to provide a further selectivity. The natural frequency of the filter is 6800 cycles per second.

A similar type of mechanical filter is used by Moore and Curtis[4] with the difference that the vibrating bar is a rod of steel, which is driven electromagnetically by the magnetic element of a telephone receiver at one end. A similar element at the other end is used as a reluctance generator. The output of this unit is amplified and applied to an instrument to indicate the magnitude of the component. The calibration is by means of a fixed-frequency oscillator tuned to the frequency of the filter, which is alternately applied through a potential attenuator, to the amplifier and output meter. The natural frequency of this filter is 11,000 cycles per second.

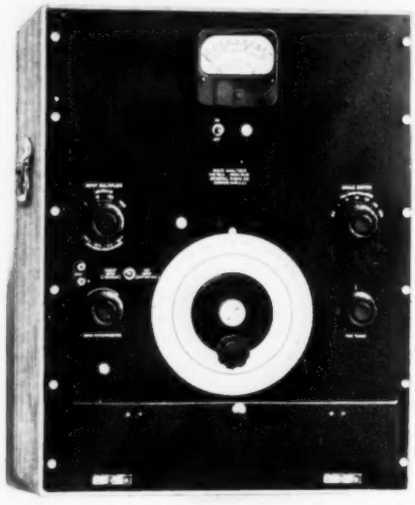

Fig. 23. General Radio Company's heterodyne type analyzer, "Type 736-A."

The magnetostrictive rod type of filter used by Hall[5] provides a sharp narrow-band-pass characteristic. This instrument is capable of separating two frequencies near 20,000 cycles displaced by not more than 100 cycles, and differing by 50 or 60 db. In the design of this instrument, to have gone to a higher frequency would have provided a better percentage selectivity but would have caused a sacrifice of actual resolving power. To have gone to a lower frequency, out of the range of the magnetostrictive oscillator, would have meant an extreme loss in selectivity.

The first attempt at building this magnetostriction vibrator made use of a nickel tube 12.5 cm. long (half wavelength at 20,000 cycles) supported at its midpoint in a cylindrical shield, divided into two parts by a shield partition. Each half of the tube contained a coil which fitted loosely over the tube. A polarizing field was provided by a horseshoe magnet placed outside the shield. When an a-c. voltage of the resonant frequency was applied to one coil the rod would vibrate in resonance and a similar voltage would be induced in the second coil.

Plotting the ratio of output to input voltage as a function of frequency to obtain the attenuation characteristics of the filter, showed that the resonance curve was not sharp enough. This action depends on the material used and somewhat on its configuration. Among the various metals that are capable of showing magnetostrictive effects, different natural decrements are found. Thus, Monel metal has a decrement of only 14 radians per second compared to 20 radians per second for Nichrome and stainless steel, and about 600 radians per second for nickel tubing. Consequently, a Monel tube ½″ in diameter with wall 0.035″ thick was used. Resonance was much sharper, but not symmetrical, probably due to extraneous modes of vibration. This was found to be so, and by using solid rod of the same diameter the transverse vibrations were almost entirely removed, and a pure longitudinal vibration resulted. Commercial samples of Monel vary in magnetostrictive properties, and the sample had to be chosen by test. The resonance curve was sharp and symmetrical, being less than 100 cycles wide at 35 db down. The heat treatment of the material and the polarizing field strength are important in determining the frequency of resonance and the sharpness of tuning. The most

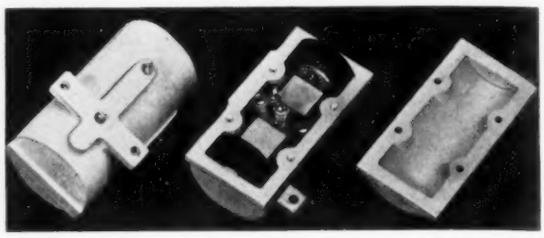

Fig. 24a. General Radio Company's crystal filter.

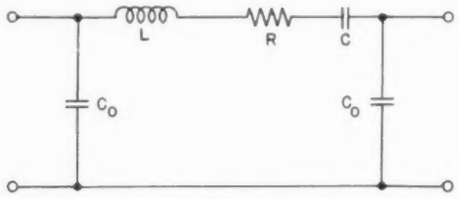

Fig. 24b.

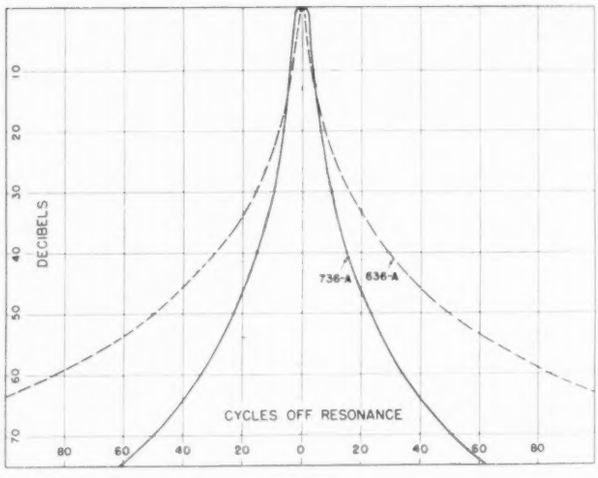

Fig. 24c.

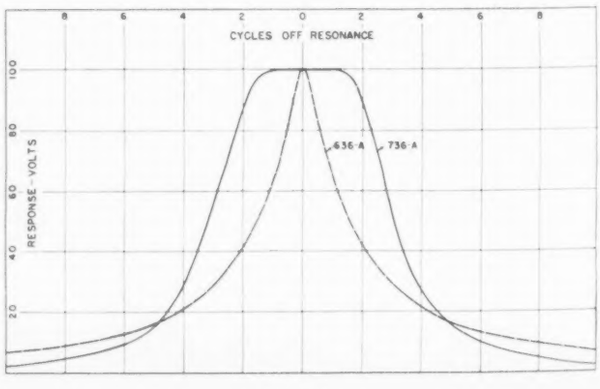

Fig. 24d.

cient coil construction takes the form of long thin coils closely clearing the bar and as close to the center of the rod as possible. A magnetic shield between the two coils is necessary to prevent direct coupling.

In order to get increased selectivity in the actual instrument, two stages of this construction were provided, coupled by a single stage of vacuum-tube amplification.

Another type of mechanical filter is the piezoelectric oscillator. Instruments employing this element are described by Gastner,[6] by Arguimbau[7] and by others. Within the past five years considerable improvement has been made in this element due to extensive experimentation, and as the result of field experience with early instruments employing crystal filters. At the time that the first models were built, it was known that crystals had satisfactory frequency and damping characteristics, but the effects on these factors of changes in operating conditions were more or less unknown. When only a single crystal is used, slight changes in the characteristics due to change in humidity and age are of little consequence, but with two or more crystals operating together there must be no differential change in characteristics. Any drift in frequency of one unit with respect to the other would be quite serious.

Since, for the extremely selective units used today, several stages of crystal filter are needed, it is necessary to design them to minimize the effects of aging. To do this, the crystals are ground to have the same frequency, but one of them is made to have a considerably higher damping than the other. This combination results in an overall characteristic which is little affected by a change in frequency of one or the other crystal of a fraction of a cycle, or a change in damping of either one.

As a preliminary step in the design of the filter unit, an extensive program of investigation was carried on to determine the action of the crystals in connection with different terminating impedances. From these results,[8] the equivalent circuit of the crystal unit was determined, from which an optimum arrangement was finally reached. In this the damping factors and frequencies of the crystals are individually adjusted by trimmer capacitors and resistors, and combined in a way to provide a narrow-band-pass characteristic.

The instrument described by Arguimbau[7] and manufactured by the General Radio Company is illustrated in Fig. 23. The crystal unit is shown in Fig. 24a, and the equivalent electrical circuit of this element in Fig. 24b. The filter unit is made up of three electrode quartz crystal filter elements. The quartz bars are plated with copper and gold to provide electrodes, and are mounted on felt in a cast aluminum frame which serves as a support, and also provides acoustic baffles at the ends to prevent damping. The aluminum castings are mounted in sponge rubber within a sealed cast aluminum housing. Experience has shown that humidity is the most important factor affecting crystal stability. Vibration tests have shown the mountings to be less critical than previously believed. Consequently, the crystals when hermetically sealed in their mountings can be regarded as fixed elements.

The response curves of the filter are shown in Figs. 24c and 24d. These compare the newer band pass, or square top characteristic, with the older pointed charactertistic. The advantages of the band pass are well known. For one thing, it becomes unnecessary to tune the oscillator for an exact maximum. The response is flat over a band of about four cycles so that when the dial is adjusted for an approximate maximum, the deflection is close to that corresponding to the true peak. This also makes it unnecessary to be continually adjusting the tuning controls. In the measurement of harmonic amplitudes of voltages which are not of absolutely constant frequency, this feature is particularly important.

Most sources of noise are generally rotating elements which are seldom driven at exactly constant speed. Any variation in speed will then show up as a change in pitch of the noise derived from it, or a change in frequency of the electrical output of the sound level meter. As an example, an airplane engine in flight is likely to vary in speed by as much as $\pm 0.5\%$. Any component of frequency of 100 cycles derived from this source will cover a band one cycle wide, and so can be measured with perfect stability by the analyzer. Higher frequencies cover a correspondingly large range, and may, if the range is too large, cause an untrue reading on the analyzer. However, the upper limit of frequency (for the case under consideration) for which the range of variation is within the band pass of the instrument, is much higher than that for the older instrument. The width of band pass used in this instrument is found to be a satisfactory compromise between the need for stability and ease of tuning, and the need for high selectivity. The complete schematic circuit of the analyzer is shown in Fig. 25.

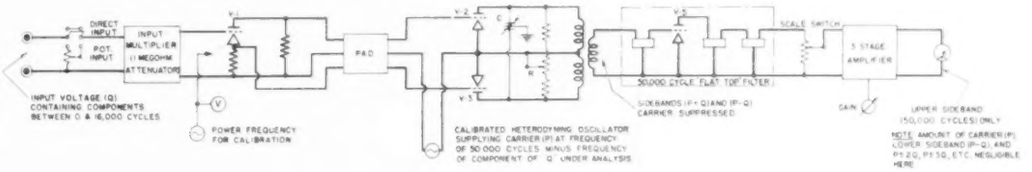

Fig. 25. Circuit diagram of General Radio Co.'s heterodyne analyzer shown in Fig. 23.

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The frequency response characteristic of the instrument described by Castner[6] is indicated in Fig. 26. This is another example of the extreme selectivity that it is possible to achieve with a crystal filter. In this instrument an additional wide band characteristic is also provided.

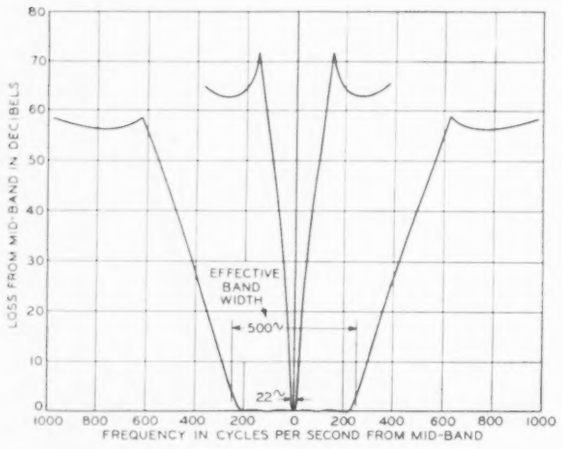

Fig. 26. Characteristics of two filters employed with analyzer described by Castner.[6]
(Courtesy *Bell Laboratories Record*)

Another type of mechanical filter used in a commercial instrument is novel in the fact that it combines in one system three stages of mechanical filtration. It is described by Mead and Berry[9] and is indicated schematically in Fig. 21. Each section of the filter consists of a small mass (or armature), spring supported from the base by means of a small shaft which is clamped at the base end. These four masses are tied together by means of fine tungsten wires wound around the shafts to rotate in unison within the limits of the springiness of the connecting wires. The equivalent circuit is shown. The clamped shafts are indicated as capacitances to ground, while the individual masses and spring of the connecting wires provide series resonance elements. The mass of the last section oscillates in the air gap of a magnetic structure. Here it provides a shifting flux through two pickup coils, and so, acting as an induction generator, gives an indication of the amplitude of response to the particular frequency applied to the filter. This filter provides a square top band pass characteristic of good selectivity.

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SECTION 13

SPECIAL TYPES OF ANALYZING INSTRUMENTS

Another type of analyzer described by Scott[1], while providing high and controllable selectivity, is operated on an entirely different principle from those previously described. In the foregoing instruments, the selectivity was obtained by the use of a tuned element which was set into resonance by a component of the appropriate frequency. This circuit has a frequency-sensitive element employing capacitances and resistances, which is non-oscillatory. It combines the simplicity of the direct-resonating type of instrument with the selectivity of the heterodyne type.

The difficulty with the electric circuit types of direct resonating instruments is the fact that in addition to their poor selectivity, they require large values of capacitance and inductance to extend their scales to low frequencies. This calls for elaborate switching and the large inductances have excessive electromagnetic pickup.

This instrument makes use of inverse feedback, or degeneration, not however as is customarily used to provide uniform wide-range frequency response, but rather to obtain a sharply selective circuit. A frequency-sensitive element, such as a bridge or similar network, which balances at a predetermined frequency, is placed in the feedback connection which provides the desired degeneration at all frequencies except the one for which it is balanced. At that frequency the voltage fed back is reduced to zero value, and the gain of the amplifier is thus raised to its

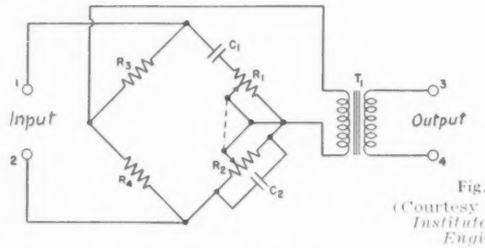
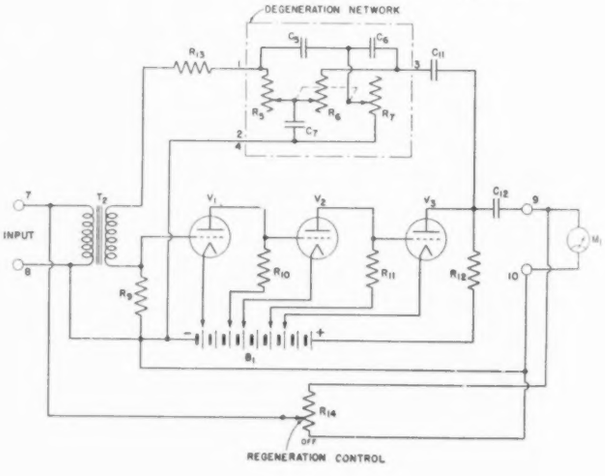


Fig. 27a.
(Courtesy *Proceedings Institute of Radio Engineers*)

Fig. 27b.



undisturbed output. At all other frequencies the amount of voltage fed back, and the phase of the voltage, are such as to reduce the gain of the amplifier to a low value.

One of the best circuits for the feedback network is that of the Wien bridge shown in Fig. 27a, which balances sharply at a frequency determined by its circuit elements which consist only of resistance and capacitance. For the configuration shown in Fig. 27a, the frequency for balance, f, is given by:

$$f = \frac{1}{2\pi \sqrt{R_1 R_2 C_1 C_2}}$$

where R_1, R_2, C_1 and C_2 are the circuit constants indicated

tting $R_1/R_2 = C_2/C_1 = 1$,

$$f = \frac{1}{2\pi R_1 C_1}$$

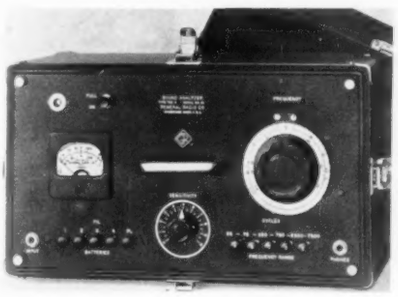
In order to avoid the output transformer, it is desirable to have a three-terminal network such as that shown in Fig. 27b. This circuit is balanced for a frequency given by:

$$f = \frac{1}{2\pi R_5 C_5}$$

for $C_5 = C_6 = C_7/2$ and $R_5 = R_6 = 2R_7$.

In this circuit the elements are of high impedance, and therefore of small size. The three resistors are ganged so that a single knob varies the frequency of balance, and so varies the frequency for which a high gain of the amplifier is provided. This type of circuit provides a selectivity which is a constant percentage of the frequency to which it is tuned, instead of being a constant width in cycles.

The feedback type frequency analyzer is illustrated in Fig. 28. Shown also is the functional circuit diagram of the general type of circuit used in this sound analyzer. This analyzer was designed particularly for analyzing machinery noises, or noises caused mainly by electrical or mechanical



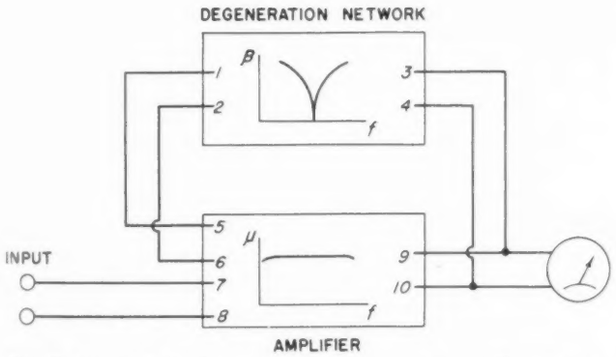


Fig. 28. General Radio Company's feedback type analyzer, "Type 760-A, and its functional diagram.

equipment. The selectivity curve widens as the frequency is increased, and so the instrument is useful for analyzing noises of machines which do not run at absolutely constant speed. It has been used successfully in analyzing the sounds of automobile and airplane motors.

Another type of analyzer[2] is that described by Theodoreson. Although operating on the heterodyne principle, it does not make use of a tuned circuit element. The principle of this instrument may be described as follows: The total heating effect in a resistance, of a number of alternating currents of given magnitude, is different, depending upon whether they are of the same or of different frequencies. For instance, if two currents, of different frequencies but of the same r.m.s. value I, flow through a resistance R, the total heating is the sum of the heating due to each current alone, being equal to $2RI^2$. If these equal currents are of the same frequency they will add to give a current of value from zero to $2I$ depending upon their phase. The heating as a result will vary from zero to $4RI^2$, depending upon the phase of the two components. Since it will be impossible to match the two frequencies exactly, the heating will vary periodically at the beat or difference frequency. The peak value of heating being twice that due to the same currents when of different frequency, as the carrier or search frequency is varied throughout the range of the audio frequency, the heating loss will momentarily increase to a larger value as the search frequency approaches the frequency of one of the components of the unknown wave.

The measurement of the heating effect may be effected by measuring the temperature (by means of its resistance) of a tungsten wire in vacuum through which the unknown and the search currents are impressed. The wire is placed in vacuum in order to avoid complications due to convection from the hot wire.

In the experimental instrument, a novel arrangement was provided in which the wire used was the filament of a vacuum tube. Its temperature was measured by means of the emission current from the surface of the filament, collected by the plate of the tube. Thus the entire process consisted of varying the frequency of the search current (which was of constant r.m.s. value) and noting when the plate current of the tube increased. The frequency and approximate magnitude of the unknown components could be inferred from this rise and the value of search frequency at which it occurred.

Barrow[3] has proposed another method of analysis of a complex wave, utilizing the heterodyne principle. This method provides a means of observing the beats produced by the combination of a search frequency which is monotonically varied, and the several components of the unknown wave. The sum of the unknown current and the search current, which is continuously varied in frequency throughout the audio-frequency range, is impressed upon a moving-

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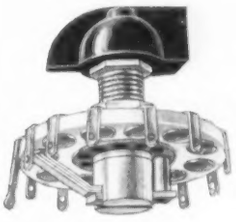

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film type of oscillograph. The rate of passage of the film is such that the individual cycles are not resolved. When the search current and the component of the unknown current have their frequencies in a simple integral ratio, a definite figure is formed on the film, the actual configuration depending upon the frequency ratio. The figures corresponding to a 1 : 1 ratio are the simplest (the actual figures differ slightly for the same ratio, depending upon the phase of the two components) and, as the numbers composing the ratios increase in size, the complexity of the figures increases. The author claims that there is little difficulty in recognizing the figures and determining from them the frequency ratios. The main advantage of this method lies in the ease with which components as close together in frequency as one cycle per second can be separated and recognized. The disadvantage lies in the fact that the magnitude of the various components is only approximately indicated.

The analysis of a complex sound by a single band pass filter requires a considerable time when sharp discrimination is desired. Analyzers with multiple resonators are cumbersome and do not cover a continuous frequency band. Meyer[4] proposed a new method based on the dispersing properties of a diffraction grating analogous to those used in optics, and equivalent to an infinite number of resonators.

There are a number of practical difficulties in such a procedure, particularly with regard to the size of the apparatus. Since the grating dimension must be of the order of magnitude of the wave-length, and since resolution depends upon the number of bars in the grating, a grating of inconveniently large size would be required for the analysis of sound throughout the entire audio-frequency range. To obviate this difficulty, Meyer has shifted the audio-frequency spectrum into a higher range by using it to modulate a carrier wave. In this range of frequency (40,000 cycles per second) the wave-length is small and the apparatus can be constructed of reasonable size. The grating is actually 3 meters long. The sound source or loudspeaker is of the ribbon type with the width of the ribbon small compared to the wave length, equivalent to a line source, so that a cylindrical wave is emitted.

This wave is diffracted by a circular grating composed of a series of steel rods equally spaced along an arc of a circle and parallel to the axis of the sound source, with the loudspeaker at the center. The detector is a small microphone sensitive in the range of the carrier frequency, which is connected to an amplifier and rectifier type of indicating instrument. The entire diffraction spectrum is covered by moving the microphone through a small arc. The output meter indicates the magnitude of the various components, and the position of the microphone their frequencies.

The main difficulty with this apparatus is the large number of bars required, and the accuracy with which they must be spaced from one another. The frequency discrimination equals that of a 125-cycle band selector. A distinct advantage of the instrument is the great speed of operation. The theoretical speed of analysis approaches 0.01 second for a complete coverage of the frequency range, and thus makes possible moving pictures of a continuously-changing sound spectrum.

Another instrument designed for rapid analysis of a complex sound is that described by Schuck.[5] This analyzer is designed primarily for rapid visual observation or recording of changing sounds. There is need for such a device, that will analyze a sound instantaneously and show the analysis immediately, so that a sound can be heard and its analysis seen at the same time. It permits immediately seeing the effects of changes and adjustments made at the source of the sound, or the effects of changes of reflecting or absorbing surfaces. It is useful also to the musician, to enable him to see the results of variations in technique.

The analyzer is a heterodyne type of instrument in which the carrier frequency is varied by automatic means, and is swept rapidly through the desired range of frequency a number of times per second. It is unique in showing visually the complete frequency spectrum of the sound being analyzed at the instant the sound is being produced. A light beam is moved in a vertical direction in accordance with the amplitude of response of the analyzer, and is moved in the horizontal direction in accordance with the instantaneous frequency of the carrier. The frequency spectrum is thus traced directly on a screen.

A balanced modulator is used to suppress the carrier. The selector is a tuned electrical network with several stages of variable damping in each circuit, and variable coupling between circuits. (See Fig. 29.) The horizontal motion of the light point is obtained by means of a mirror in the path of the light controlled by the position of the tuning con-

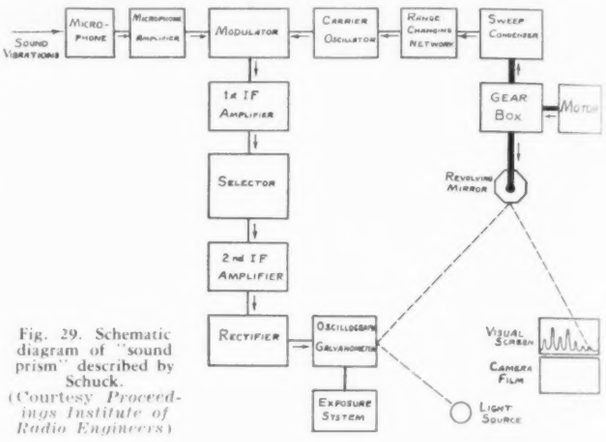

Fig. 29. Schematic diagram of "sound prism" described by Schuck. (Courtesy *Proceedings Institute of Radio Engineers*)

denser. The instrument is designed for a complete scanning, or operation throughout the whole audio-frequency range, ten times per second. Persistence of vision permits the path of the spot to be seen as a steady line of light, which changes in character only when the sound changes, and which follows all variations in the composition of the sound. Because of the great speed of operation, the use of a logarithmic amplifier, controlled as it is by a rectifier and filter, is out of the question. So a linear scale of intensity is recorded as a function of frequency. Some attempt has been made to obtain the logarithmic scale of the output current in a simpler more direct way which will permit faster scanning, although no suitable method is available at present. There is another difficulty in the operation of this instrument with its rapid change in frequency: the transient action of a resonant element when used as a detector and supplied with a current of rapidly-changing frequency is not fully known, and consequently it is possible to obtain false indications if the proper range of scanning frequency is exceeded.

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SECTION 14

MISCELLANEOUS NOISE INSTRUMENTS

Integrating Noise Meter.

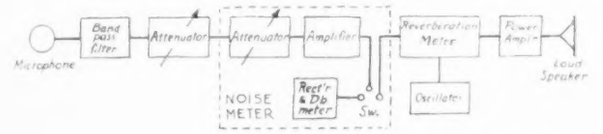
One step removed from the indicating type of noise meter is the integrating noise meter proposed by Haynes.[1] In this instrument, in place of the customary indicator, he has provided a watthour meter which will indicate the integrated output of the sound meter amplifier. The circuit is quite simple, consisting of a vacuum tube, with a-c. voltage ap-

...d to the plate, and the current element of the watthour ...ter in this circuit. The potential element of the meter is f... from the same constant-voltage a-c. source. The output ... the sound meter amplifier is applied to the grid of the am...fier tube. Although the torque acts only on alternate half-...cles due to rectification in the tube, the output is propor...nal to the time integral of the voltage applied to the grid, and thus to the time integral of the sound level at the ...crophone.

Portable Reverberation Meter.

Another type of acoustical instrument closely related to the sound level meter is the reverberation meter described by Sabine.[2] By definition, the reverberation time of a room is the time in seconds for a sound set up in the room to decay naturally by 60 db. In this instrument the noise meter is used to indicate a change in noise level of a fixed, though unknown, amount. The time for this change is recorded and, by means of an attenuator, this interval is changed by a known amount. The difference in decay time and difference in total decay serve to indicate the slope of the decay curve, and so the reverberation time.

The instrument consists essentially of an ordinary sound level meter with a logarithmic attenuator which can be connected to a reverberation meter. The output of the sound amplifier is applied to a stage of amplification and rectification, which is applied as a bias in the grid circuit of a thyratron tube. The latter controls a relay that switches



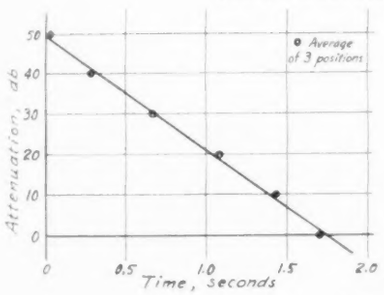


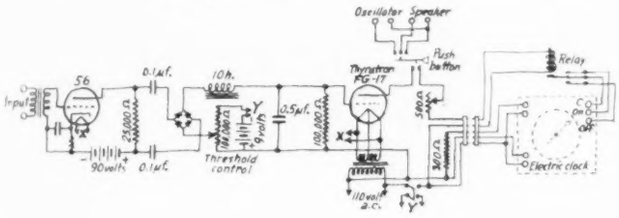
Fig. 30. Reverberation meter described by Sabine[2].

(Diagrams redrawn by permission from *Electronics*. Modified by ed. staff of *Instruments*.)

Above — Functional diagram.

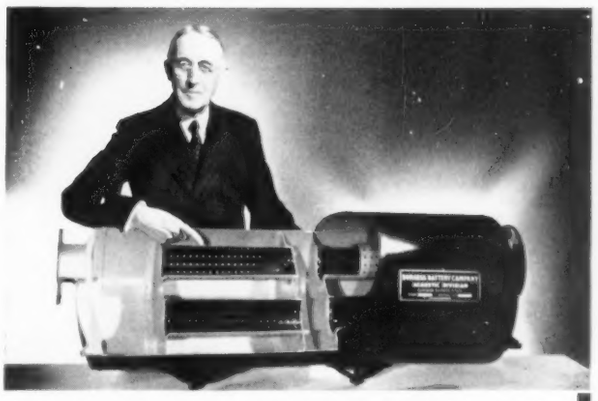
Left—Typical curve of results of reverberation measurements in a large acoustically - treated church.

Below—Circuit diagram.



an electric clock into the circuit and so counts the time that the thyratron is excited. A loudspeaker is used to provide a fixed though unknown initial sound level in the room. When the loudspeaker is turned off, this thyratron circuit is switched into operation. When the sound level drops to a value too low to keep the thyratron conducting, the relay drops out and the clock stops. This time is a measure of the interval between the original level of sound, and a final unknown level (corresponding to the least exciting grid voltage on the thyratron). If the attenuator on the sound meter is then changed by a given amount, and the operation repeated, the clock is shut off earlier or later by a time corresponding to the decay over the fixed number of decibels. When this process is repeated several times, the measured intervals plotted against the various settings of the attenuator, and the resulting curve extrapolated to cover a range of 60 db, the time interval corresponding to that change in intensity is the reverberation time for that room.

The circuit of this instrument is shown in Fig. 30. The a.c. is applied to the plate of the FG17 thyratron tube which



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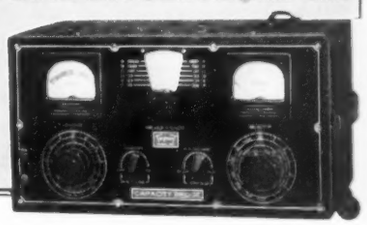

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is made conducting as long as the sound level is above a certain minimum value set by the attenuator and the characteristics of the tube.

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[2]H. J. Sabine, Portable Reverberation Meter, *Electronics*, Vol. 10, Mar. 1937, pages 30-31, 35.

SECTION 15
APPLICATIONS OF NOISE MEASURING INSTRUMENTS

In the application of noise measuring instruments to the solution of noise problems, the important fact will be recognized that almost every noise problem is different from the others, and where one type of instrument is useful, another may be entirely out of place. Different problems will call for different types of instruments, or at least, different forms of the same instrument. Thus, the total sound meter finds extensive application in simple sound measurements, and in the study of the acoustical properties of rooms: The results of different placement of sound absorbing material, the use of different materials, and the results of a change in placement of sound sources, are immediately detected by the use of the total sound meter. But in the study of machine noise, the problem of change of design or operation in order to reduce the noise from a machine involves the use of frequency analyzers. If the sound has components that are pure tones reasonably constant in pitch, the analyzer is extremely useful. However, most machines produce a noise that is mainly unpitched sound, and this may form the most prominent or objectionable part of the noise. In such a case, some sort of band analyzer, or special frequency weighting, is more useful. This likewise happens if the speed of the machine producing the noise varies, for then the frequencies of the components change, and a sharply-tuned frequency analyzer is likely to be of little use.

Acoustical measurements are most valuable when they are correlated with other knowledge of the machine under study. Changes in design involving different parts, or different methods of connection, or measurements of the internal action, or peculiarities in the methods of manufacture, are all useful in explaining the change in noise producing character of the machine. And the acoustical engineer must work closely with others concerned with the development and design of the machine in order to be better able to plan his investigation.

A noise survey of a machine or group of machines is generally made for the purpose of reducing the total noise from these machines. It is important at the outset to realize that the total noise may be made up of a number of components, any one of which may alone be almost equal in magnitude to the total noise. Yet with the elimination of that one component the reduction in total noise may be almost unnoticeable. It is a law of the decibel scale that two pressure levels of whatever magnitude, when added, cause an increase of the total level of only 3 db. And two sounds individually of 80 db when sounded together provide a noise level of 83 db. Thus there would only be a reduction of 3 db by removing one source entirely. For practical purposes, to reduce any component by 10 db or more is as good as removing it entirely, when there are several sources contributing to the total noise.

The rule of combination of individual sound pressures to obtain the total sound pressure, is the square root of the sum of the squares of the individual pressures. This can be done by means of the formula:

$$db = 20 \log_{10} P_2/P_1$$

where db is the pressure level in decibels;
P_2 is the actual sound pressure, and
P_1 is the base or reference pressure.

The actual pressure of each component is obtained from its db level, and the total sound pressure determined arithmetically, which is then converted into pressure level above the same base or reference pressure.

However, this operation can be done more quickly and easily by means of a curve such as that shown by Abbott[1]

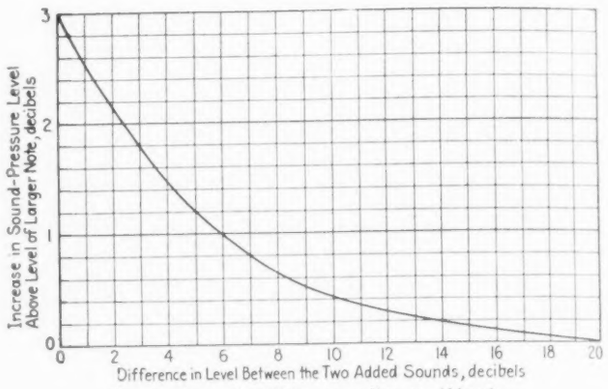

Fig. 31. Law of addition according to Abbott[1].
(Courtesy *S.A.E. Journal*)

and reproduced in Fig. 31. The abscissae are the differences in level between the two components to be added, in db, and the ordinates are the increase in sound pressure level above the level of the larger, in db. For example, two sounds of equal pressure level (zero difference) combine to give a total 3 db higher than either one.

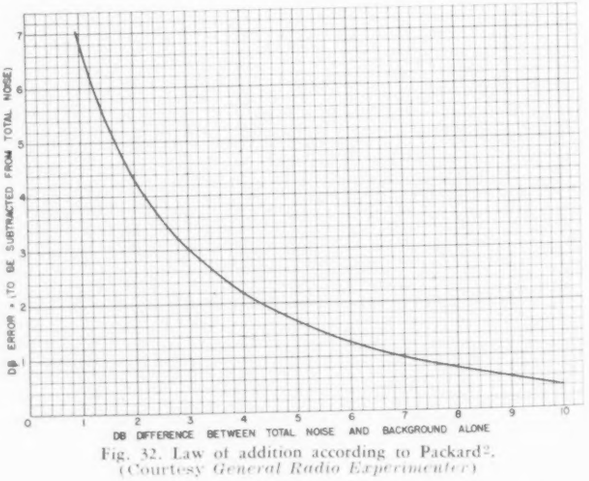

Fig. 32. Law of addition according to Packard[2].
(Courtesy *General Radio Experimenter*)

A similar type of curve, though arranged in different form, is shown by Packard[2] and reproduced in Fig. 32. In this curve the abscissae are values of db difference between total noise and background alone, while the ordinates are the values of db error in the indication of the total sound meter (and are values to be subtracted from the values of total noise, to indicate the level of the noise without background). In the case above, consider that one of the components is background noise, and the other is machine noise. It was shown that the sum of the two was 3 db above either one. Thus the abscissa in this curve would be 3 db, which corresponds to an ordinate of 3 db. This shows that the actual machine noise is 3 db lower than the total sound level.

The particular value of the curve of Fig. 32 lies in its use when the noise to be measured is heard in conjunction with a fixed background noise. Normally, it is most desir

ge to test a machine for the amount of noise it produces in a sound-proof room, and any machines that are small enough to be portable are generally so tested. Fig. 33 shows a special sound-proof booth for testing small motors. In plants making large machines, however, a sound-proof room is either unavailable or impractical, and it is necessary to make sound measurements under existing noise conditions. Sometimes this situation can be handled by the use of a vibration pickup. If a microphone is used it is advisable to reduce the level of extraneous noise to as low a value as possible and to make separate measurements of the background noise alone and of the total noise of background plus machine noise. Then by means of the chart (Fig. 32) the difference of the two is entered and the correction read off. Due to the steepness of the curve in the region of small db differences between background and total noise level, considerable error can be made in the value of the machine noise, and this method becomes impractical when the machine noise is small compared to the background.

In general, the benefits from the reduction of component noises that are more or less equal in intensity, are not to be had by the entire elimination of any one component (for as can be seen from Fig. 31 a component 10 db lower than another can only contribute 0.4 db to the total), but by the partial reduction of all contributing factors. This is discussed by Zand[3] for the case of the noise reduction of airplanes. In the airplane which is discussed there are a number of important contributing factors, such as the propeller which supplies a noise level of 108 db, the exhaust with a noise level alone of 104 db, the engine and gear noise of 90 db, the aerodynamic noises of 88 db, the air-borne noises of 85 db, and the ventilating noises of 95 db. The actual total noise level is only slightly more than the largest component, or 109.9 db. Reducing the exhaust noise entirely will only drop this total noise level down to 108.7 db. However, by careful consideration of all possible causes of noise, and improvement in design, each contributing source of noise can be reduced several db, and the total noise level can be reduced to 95 db. This is still an extremely high value of noise level, but it represents a reduction in noise energy of 97.5% from the original condition.

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SECTION 16

INTERFERENCE PATTERNS.

In making noise measurements in any other than a sound-proof room, more or less difficulty is experienced from wave patterns. If the machine is large enough so that several parts or surfaces displaced a distance comparable with the wave-length are vibrating at the same frequency, or if there is a considerable area of highly-reflecting surface nearby, then the sound field set up by the machine will not be uniform. There will be points of maximum and minimum intensity spaced throughout the volume, which must be taken into account if the noise due to that particular machine is to be measured properly.

In cases where the sound set up has a distinct interference pattern, the sound level meter may show a difference of 10 to 20 db in its reading when its position is changed only a few inches. If the machine speed is constant, readings at any one point are reasonably constant although different from those at other points nearby. This is due to the phenomenon of interference. Physically it amounts to the condition that at a given point, two wave trains of the same frequency may be passing. If these are in the same phase, that is, if the sound pressure reaches a maximum at the same time, the actual maximum sound pressure at that point will be a function of the sum of the two maximum pressures of the individual trains. The pressure level at that point will be higher when both wave trains are passing than when either one is passing alone. If the two wave

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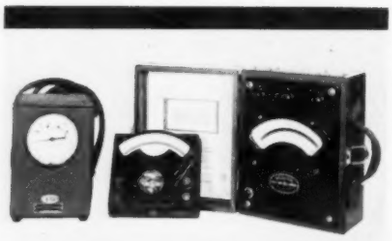

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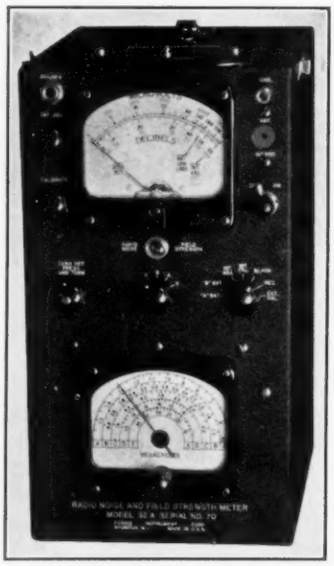

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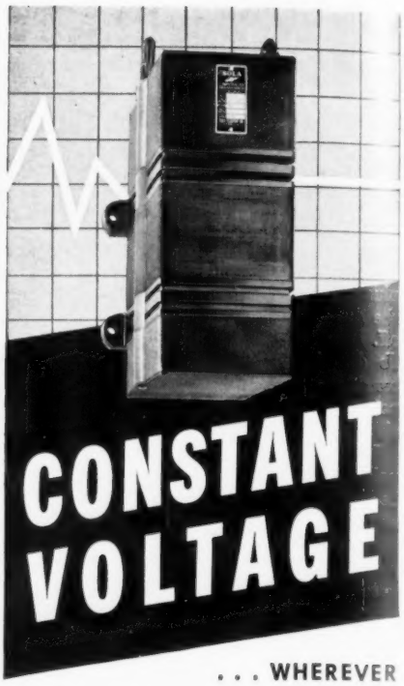

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ns arrive at that point in opposite phase, one wave will tend to cause an increase in pressure at the same instant that the other tends to reduce the pressure. The actual peak pressure will then be less than that of the wave of higher sound level, and much less than the peak pressure at other points in the field. Thus the actual sound pressure level at any point in the sound field depends upon the number, and relative phase, of the wave trains passing that point.

The wave pattern around a given machine under given conditions is surprisingly constant as long as the conditions are maintained; but the patterns are easily changed. A small change of speed changes the pitch and thus the wavelength, and the pattern is entirely shifted. The average sound pressure over a region may not be changed, but the readings of the sound pressure at particular points will change. If the reflected waves from adjacent walls and objects are the primary cause of the wave pattern, a shift in position of the source or of any of the reflecting surfaces (which may be some person or object in the neighborhood of the machine) will cause a change in the interference pattern. Even machines which may be mechanically identical will not show the same vibration pattern, and will show a different interference pattern, when placed in an identical position with respect to reflecting surfaces. Consequently, even in the case of identical machines it is impossible to depend upon a single reading of sound pressure level at a given point with respect to the machine, as a measure of the noise level due to that machine. It is necessary in all cases to take sufficient readings at different points and average them, to obtain a representative value of the sound pressure level for the machine.

If it is desired to determine which of the parts of the machine is causing a particular noise, it is necessary to have a noise analyzing instrument. With the machine speed held constant (for which purpose a stroboscope is useful) the frequency spectrum of the noise is taken. This is compared with the vibration spectrum determined by means of a vibration pickup placed in turn, on all the vibrating parts of the machine. Since the sound wave must be set up by a vibrating surface, it is possible to pick out one or more surfaces or portions of surfaces which are possible radiating surfaces for that wave. However, it does not necessarily follow that these surfaces are the cause of the noise. Vibrations may be set up in remote parts of the machine and be transmitted to the radiating surfaces. It is necessary to have fairly large surfaces and large amplitudes, in order to radiate an appreciable amount of energy. Large flat surfaces of the machine could readily act as radiating surfaces if excited at their natural frequency, for at resonance their amplitudes of vibration are highest. In many cases excellent agreement has been had between the frequency analysis of the noise from a given machine, and markings which were found on gear teeth for example, when the machine was dismantled for inspection.[1] Spots showing abnormal tooth contacts were found spaced around the periphery of the pinions in groups which corresponded exactly to the frequencies of the observed notes.

In cases where there is a definite wave pattern about the machine it is futile to try to obtain comparative noise ratings at a single point, unless means are taken to remove the interfering waves, or to average out their effects. There are three common methods available for taking care of this: (1) To take sufficient readings around the machine, so that by averaging them a satisfactory sound rating of the machine is had. (2) To use an acoustically treated room in which the walls are highly absorbent, so that only direct sound is measured by the microphone. If there are a number of radiating surfaces, or if the machine is large, there may still be an interference pattern. (3) To use a sound chamber with highly reflecting walls, and to provide a series of rotating paddles of steel or other highly reflecting material. The constant change in the geometry of the reflecting surfaces prevents the formation of any fixed wave pattern. If the microphone is rotated with the paddles, and if the indicating meter has a long enough period, it will average the sound pressure level throughout the room and give a useful rating of the machine. Sometimes just rotating the microphone throughout a considerable portion of the space will serve the same purpose. This is really physical averaging of the individual pressure levels at the large number of points on the path of the microphone, compared to mathematical averaging of the readings taken at a number of discrete points.

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SECTION 17
METHODS OF QUIETING MACHINES.

In any program set up to reduce the noise of a machine, the first step is to determine the relative importance of the various components of the noise and the reduction in the total which may be had by maximum reductions in these components. This will indicate that some components, while of considerable magnitude, contribute only slightly to the total. Concentrating on those which supply a large part of the total sound energy and are most susceptible to reduction, efforts should then be made to reduce the several component noises. The ways in which reduction in radiated noise energy may be accomplished may be listed as follows:

1. Mismatching of vibrational impedance,
2. Reduction of radiation resistance,
3. Enclosure,
4. Acoustical absorption,
5. Use of mechanical damping resistance,
6. Greater accuracy of parts,
7. Shifting of frequencies to other ranges.

1. Mismatching of Vibrational Impedance. It is possible to have filters in mechanical systems just as in acoustical or electrical systems. These are generally not known by this name, but are called isolators, or balancers, or any other such name which indicates a particular action. However, any filter is constructed of a network of oscillatory elements which are tuned to definite frequencies. Thus, in electrical systems, a series resonant element acts as a low impedance path for vibrations of the frequency to which it is tuned. Similarly, parallel resonant elements provide a high impedance for frequencies to which they are tuned. By including elements of this type in the mechanical system it is possible to change the vibrational impedance of the system so as to cause obvious mismatching, and so isolate certain frequencies within the system.

Experience indicates that this is one of the most generally applicable means of effective and economical quieting of machinery. It can often be brought about by only minor changes in design. Among numerous examples of applications of this principle is the harmonic balancer for engine crankshafts.[1] This generally consists of a pivoted mass restrained by torsion in a spring, and provided with some sort of mechanical damping. This element, in effect, provides a mechanical short-circuit on the vibromotive forces generated in the crankshaft. Vibrations of the proper range of frequency are absorbed in the oscillatory element and there dissipated as heat in the resistance, and are thus prevented from being transmitted to other parts of the system. Numerous designs of rubber and spring motor supports are in common use.[2] These make use of an oscillatory system of low frequency which effectively isolates the machine from the base. The automobile exhaust muffler is another example in which a low-pass acoustical filter is provided, which offers no impedance to low frequencies (and permits the free passage of exhaust gases) but provides parallel resonant chambers in which the higher frequency waves are trapped and their energy dissipated.[3]

2. Reduction of Radiation Resistance. Radiation resistance is the term which indicates the ability of a mechanical system to convert mechanical vibrations into acoustical vi-

brations. In a loudspeaker, the small piston (to which the coil is fastened) is too small to effectively radiate acoustical energy, so it is coupled to the atmosphere by means of a large diaphragm, cone, or horn, in order to increase its ability to radiate sound energy. Similarly, though unintentionally, all mechanical surfaces because of their size and shape have greater or less ability to radiate sound energy if they are vibrated. In general, the sound that reaches the ears of the observer is radiated from some surface; and hence depends upon how the surface vibrates, its shape, and its dimensions. Furthermore, since most surfaces are vibrated and radiate as a result of resonance, it is possible by means of mechanical resistance to damp the vibration, and so, reducing the amplitude, to reduce the sound energy radiated. Also, by mounting large surfaces so that they are isolated from the source of the vibrations, they are prevented from vibrating in sympathy.

3. Enclosure. If a sound-proof box is placed around either the source of sound, or the observer, the noise reaching the observer is greatly reduced, particularly if the box is itself free of vibration. Considerable time and money has been spent in the past few years on the development of sound insulating materials of light weight and cheap construction which can be used to effectively insulate against unwanted sounds. A good partition alone will cause a reduction of 20 to 30 db or more in the air-borne sound. The design of such an insulation chamber involves several points, among which may be mentioned the following: (1) it is necessary to isolate the partition, or room, from the source of mechanical vibrations; (2) there must be no panel vibration of the walls, and (3) acoustical absorbing material may be used inside the room. For example, if the room is to surround the observer, the actual sound level is a function of the transmission qualities of the walls and of the absorptive qualities of the material in the room. Obviously, if there were no absorptive material in the room, the small amount of energy that might be transmitted through the walls would never be absorbed, and the sound level in the room would remain at a high value.[4]

4. Acoustical Absorption. In many cases effective noise reduction is possible by the use of acoustical absorption. The most important example is the use of absorptive material in the acoustical treatment of offices, homes, theaters, etc. If the source of energy is fixed, or the amount of sound energy transmitted into the room is fixed, the final noise level in the room can be reduced by the application of sound-absorbing material. Of course, this method is most effective when it can be used to treat a passageway through which the sound is being transmitted, or where the sound can be absorbed by the material before it reaches the ears. Familiar examples of these types of applications are the type of automobile muffler which uses absorptive material surrounding the central pipe (and communicating with it through a number of small holes) through which the exhaust gases are driven. Another is the acoustical window ventilator which consists of an acoustically treated passage through which the air is drawn. Another is the acoustical treatment of air-conditioning ducts to reduce the sound energy carried into the room.

Unfortunately, most absorptive materials are most effective at frequencies of 500 to 2000 cycles, and are relatively ineffective at the low frequencies of machine noise. However, materials with special characteristics have been developed for individual applications. These materials do not all offer the permanence and wear resistance of standard types of building materials, although some of them do compete remarkably on the basis of looks, wear, and permanence. Although the fact still remains that it is most desirable, where possible, to reduce the source of the noise rather than provide absorbing material to dissipate it, the use of sound-absorbing material is a useful tool in the control of noise.

5. Use of Mechanical Damping Resistance. Mechanical friction is normally something to be avoided. In most machines much time and money is spent to remove all possible sources of friction. Yet there are times when it is desirable to introduce mechanical friction, such as in the reduction of vibrations. The presence of resistance is most useful in the reduction of vibration for transients, and for frequencies in the region of resonance. Vibration dampers of all sorts make use of resistance or friction to dissipate vibrational energy.[5]

Large panels such as walls and doors are damped in order to avoid prolonged vibration when subjected to shock excitation.[6] This is easily accomplished by the application of viscous material to the panel surface, as is done to a considerable extent in automobile and aircraft work in which so much use is made of thin-panel materials. The amplitude of forced oscillation is greatest at resonance. Since mechanically this is the frequency for which damping is most effective in the reduction of amplitude, it is possible by the use of friction to damp such vibrations and materially reduce the sound energy radiated.

6. Greater Accuracy of Parts. In general the noise that is emitted by a machine is an indication of the value of the design and construction. The improvement of a machine in this respect does not lie in the use of extreme care in the construction so as to limit motions, or in setting up smaller tolerances in the construction, for the amplitudes of vibration which may cause extremely high noise levels are measured in dimensions which are smaller than the tolerances which can economically be kept. The solution lies primarily in the design, particularly with respect to the types of structures and contacts. Most noise (except where obviously due to play in parts) is due to vibrations which are the result of the non-rigid nature of the materials from which the machine is constructed. The design must tend to overcome this weakness of material by the proper choice of shape size and section to avoid all flexible parts and large unsupported surfaces.

7. Shifting of Frequencies to Other Ranges. Since the amount of sound radiated from a surface depends upon the shape and area of the surface among other things, it is possible by controlling these factors to lessen the amount of sound radiated from the surfaces. By change in design of the radiating surfaces they can be made of higher or lower natural frequency, so that they are definitely out of range of the frequencies set up by the machine when normally running. Thus their amplitudes of vibration will be less and the amount of energy radiated will be less. This same effect can be had by changing the design of the machine, such as by change in structure, or by change in the speed of certain parts, so that the normal vibration frequencies are out of range of the resonance frequencies of the vibrating surfaces that radiate the noise. Another effect of the reduction in frequencies of vibration is that the radiation efficiency of the vibrating surfaces is less for the lower frequencies. Furthermore, the sensitivity of the normal ear is much less at the lower frequencies, and sounds of the same energy will be less loud and consequently less objectionable.

In many cases it costs no more to build a quiet machine than to build a noisy one, and a quiet machine cannot be had only by the addition of acoustical treatment to an otherwise noisy one. The quietness is part of the design, and must be built into the machine. There are many possible ways of doing this, as outlined above, and it is simply a question of determining the most economical way of obtaining a given reduction in radiated energy. Toward this end acoustical measurements provide an effective and direct means of doing this work, and lead to a solution which would be impracticable of attainment without the use of acoustical instruments.

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SECTION 18
CONCLUSION

All of these acoustical instruments are convenient tools for the recognition and measurement of sound waves. However, they must be used with a complete knowledge of their background, and of the problems in hand. While their use in electrical measurements is simple and precise, this is not the case in acoustics where there are so many disturbing factors. It requires an understanding of the basic theory of acoustics to recognize exactly what it is to which the instruments are responding. The difficulty of controlling sound waves, the results of refraction and diffraction, and particularly the apparent inconsistencies that are the result of interference, are disturbing.

There is even some question as to whether instrumental readings are of any value at all. Since instruments cannot entirely duplicate the ear in loudness measurements, and since in all noise problems the ear is the final judge, the question is often asked: Why use instruments at all?[1] However, in spite of this attitude on the part of some workers, much has been accomplished and reported in the technical press on the use of these instruments in the study of particular noise problems. These results serve to illustrate the degree of ingenuity required for the use of noise measuring instruments.

Sound measuring instruments have been used for an extremely wide range of problems, from the detection of airplanes and submarines in time of war to the measurement of the altitude of airplanes[2] or the depth of the sea,[3] to the measurement of the noise from machines,[4] electrical equipment,[5] fans,[6] automobiles,[7] and airplanes,[8] to production problems,[9] to the study of musical instruments and communication equipment,[10] and to a large number of similar problems. The technique[11] developed as a result should be a convenient starting point for any further investigations to be made in the field of noise measurements.

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APPENDIX I
THE DECIBEL SCALE

In ordinary numerical work a change in a given quantity is usually expressed in the same units as that quantity, or as a percentage of that quantity. Thus, a drop of voltage in a line from 100 volts to 90 volts would be indicated by a drop of "10 volts," or a drop of "10%," or the expression of the terminal voltage as 90% of the input voltage. If there is a second circuit element following the line, in which the drop is 9 volts, this second element has a loss of 10% also, and its output is 90% of its input. The final output of the system is 0.9×0.9 or 0.81, or 81% of the original input, and the loss in voltage is 100 $(1 - 0.9 \times 0.9)$ or 19%. In circuits containing many series elements it is convenient to perform this multiplication by the use of logarithms.

This process has found considerable use in telephone and communication practice in general. In this work there are numerous types of circuit elements through which the loss or gain of power is in fixed ratio to the input power, irrespective of the part of the circuit in which they are placed. The unit which expresses the ratio of power output to power input is the *bel*, or the smaller unit, the *decibel*. The decibel is defined as:

$$\text{db} = 10 \log_{10} \frac{\text{Power Output}}{\text{Power Input}}$$

If the output power is less than the input power the expression is negative and the *loss* is said to be so many db. If there are a number of circuit elements in series, the overall loss or gain of the system is arrived at by simple addition of the decibels for each element, with proper attention being paid to the sign.

The decibel scale was developed as a matter of practical

convenience, and its value has long been demonstrated in telephone work. Consequently its adoption in sound work was quite natural. And in this work it has several additional advantages:

1. The ear has such an enormous range of sensitivity that to express it in terms of the energy or pressure would require numbers of a size inconvenient to handle. The logarithmic unit is much more convenient for this purpose.

2. The action of the ear is approximately logarithmic. In other words, doubling the energy of a sound does not increase the loudness in the same ratio, but more nearly as the logarithm of that ratio. Consequently, expressing the energy or the intensity in logarithmic units provides an approximate scale of loudness.

3. Data taken by several observers in different units can be converted for comparison more readily when expressed in logarithmic units than when expressed in ordinary units. To compensate for the difference in reference level requires only the addition of a fixed number representing the decibel difference between the two reference levels.

In the decibel scale the answer is always given in terms of the differences in decibels, never the ratio, or percentage change. This is an unusual concept for one not familiar with the system, but its advantage is easily demonstrated. It follows from the definition of the decibel that one decibel simply represents a pressure ratio equal to the 20th root of 10, or a ratio of 1.12. In other words, two sounds differing by 1 db have their pressures in the ratio of 1.12 to 1. Similarly, two sounds differing by 20 db have their pressures in the ratio of the 20th power of 1.12, or 10 to 1. If two sounds of equal pressure level are added, it means that the sound energy is doubled, and the number of decibels change is given by 10 times the logarithm of 2, which is 3 db. Thus the sum is always greater by 3 db than the original level, no matter what the original level. This procedure is equivalent to adding sound pressures according to the square root of the sums of the squares, and makes the energy of the sum equal to the sum of the energies of the components.

While the decibel has been in common use in this country for several years as a unit of intensity level and loudness level, some European observers have made considerable use of the *phon* as a unit of loudness level. Realizing the value of two separate units for the actual energy and the subjective response, the International Conference on Acoustics held in Europe in 1938 agreed that the unit to be used for intensity level measurements shall be the decibel, but the unit to be used for the equivalent loudness level measurements shall be the phon.

Loudness measurements are to be made by listening to the reference sound and the sound to be measured alternately with both ears, while the intensity of the reference sound is regulated until an ordinary observer considers that it has the same loudness as the measured sound. Whenever possible, the reference sound and the one to be measured should be listened to for practically the same length of time. This period should never be shorter than one second when listening to the reference sound. When, under these conditions, the intensity level, or the pressure level, of the reference sound is "n" decibels above the reference zero, it is said that the sound measured has a loudness level of "n" phons.*

APPENDIX II

TEST CODE FOR APPARATUS NOISE MEASUREMENTS

The subcommittee on Sound of the A.I.E.E. Standards Committee has prepared a test code† for noise measurements, published in March 1939. Indicated purposes: (1) For use as a guide in the measurement of sound levels and the investigation of various elements contributing to the total noise produced. (2) To aid in settling questions that arise after equipment is installed as to the true causes of the observed sound level, and the best way to reduce it. In such cases it often is desirable to design apparatus for a given installation to meet a specified sound level. This requires knowledge of the sound produced by the apparatus and of the effects on the sound level of reflections and absorption due to the ambient conditions. (3) To establish reasonably uniform methods of conducting and reporting such sound level tests, so that wherever or by whomever tests are made, the results will be of value for record and will be truly comparable with tests made at other times and places.

This code discusses briefly (1) General Considerations on Apparatus Noise Measurement, (2) Radiation of Sound, (3) Room Effects, (4) Ambient Sound Levels, and (5) Instrument Standards, and sets up specific instructions for (1) Factory Tests, (2) Standard Factory Measurement Positions, and (3) Field Investigations.

In factory noise investigations, measurements should be made under such conditions that the increase in the measured sound level produced by reflections from surrounding surfaces is small. Microphone should be placed in a position free from disturbing air currents, vibrations, electric or magnetic fields, or other external influences which may affect readings. If possible, the ambient sound level at the test location should be at least 6 db, and preferably 10 db, or more, lower than the sound level due to the apparatus. In general, this requires a special noise box or room with sound-absorbing material placed on the floor, walls, and ceiling. Corrections for ambient levels in factory tests are not generally permissible due to frequent erratic variations.

Where possible, to insure measurements of air-borne noise only, resilient means should be interposed between the device being measured and its support.

Measurements should be made at several locations near the apparatus to obtain a close approximation to the average sound level produced by the apparatus under free field conditions. To obtain an average sound level figure from a group of sound level readings taken around a machine, the average shall be obtained by the energy average method. The energy average is defined as $10 \times \log_{10}$ of average of the antilogarithms of 1/10 of the separate db values. In most cases, where the range of the readings to be averaged is of the order of 12 db or less, the arithmetic average of the db readings is sufficiently close.

When reporting sound level measurements, the dimensions of the room and the nature of the floor, walls, and ceiling, the sound level of the room, the condition of operation of apparatus under test, the position of the microphone, and the frequency response of the sound level meter should be recorded. The type of mounting and other information indicative of the degree of transmission of sound to the supports is also important.

In connection with actual factory noise measurements, it is suggested that one of three standard distances (6", 1 ft. and 3 ft.) from the microphone to the apparatus be adopted. These distances should be measured to the nearest major surface.

In the field investigations of the same apparatus, the first step should be, if possible, to measure the sound level produced while the apparatus is in operation with the microphone placed at the standard factory test positions. In any case the positions should be chosen so near the apparatus producing the noise that the effects of wall reflections or other environmental conditions are a minimum. Then the ambient sound level is measured with the apparatus shut down. The actual procedure then depends upon the level of the apparatus noise relative to that of the room. In particular, for the case of:

(1) Apparatus noise much lower than the ambient noise, indicated by the fact that there is no change in reading when the apparatus is shut down. The readings of the apparatus noise in this case are not correct, and indicate only that the apparatus noise does not exceed ambient noise level.

(2) Apparatus noise higher than ambient noise. If the apparatus noise is more than 6 db above the ambient level, the ambient has little effect on the total noise level.

(3) Apparatus noise of the same order as ambient noise. Under these conditions the sound level of the apparatus may be approximated by the use of the curves shown in Figs. 31 and 32. These are based upon the fact that the sound level meter adds the weighted energies of the various sounds that reach the microphone.

The effects of wall reflections and other environmental conditions may be determined by comparing readings at different positions in the vicinity of the apparatus with those at the standard positions. If the reduction of sound level with respect to distance deviates considerably from that obtained under free field conditions, or if marked variations in sound level occur from point to point, sufficient measurements should be made to establish the general character and location of local increases in sound level. These may be produced by reflecting surfaces, structure-borne noise transmission, focal points of reflections, etc.

*H. Fletcher, Noise Measurements and the International Conference on Acoustics, *Bell Laboratories Record*, Vol. 16, 1938, page 213.

†Test Code for Apparatus Noise Measurement, American Institute of Electrical Engineers. Approved by A.I.E.E. Board of Directors March 7, 1939. A.I.E.E. Publication No. 520. Price 30 cents.

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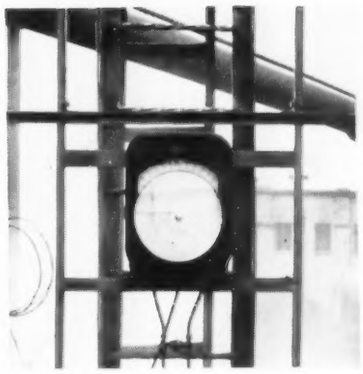
Goggles with Absorptive Lenses for Glass Blowers, etc.

For glass blowers there is announced a new type of goggle consisting of a rhodium spectacle frame equipped with Neophan Absorptive Lenses which absorb the intense yellow radiation (sodium line) and enable glass blowers comfortably to view work under the flame. Lenses prevent eye strain, are slightly curved, and are said to be "ideally suited for sensitive eyes." They may also be had in clip-on style for persons regularly wearing glasses. New glass, while absorbing sodium line, does not change rest of visible spectrum. Neutral pinkish tint of lenses does not affect visibility and goggles may be worn "with perfect comfort" for general utility.—*Fish-Schurman Corp., 250 East 43rd St., New York City.*

Shop Measuring Microscope

New model Leitz Shop Measuring Microscope is normally mounted on a heavy base plate but may be removed for use as a self-contained unit in machines or fixtures.

Designed for measurements in one linear direction, it has a 2" range by micrometer screw with dull chromium finish drum divided directly in 0.0001". Split nut within micrometer slide may be disengaged, so that for larger distances a rapid traverse independent of the micrometer screw is available. Microscope has an inclined ocular, containing hair-line cross, with means for centering eye-piece co-axially. Rough focussing is by rack and pinion; independent fine focussing by a second knob with graduated dial whereby it is possible to obtain positive depth measurements, by using an objective of higher power.—*George Scherr Co., 128 Lafayette St., New York City.*



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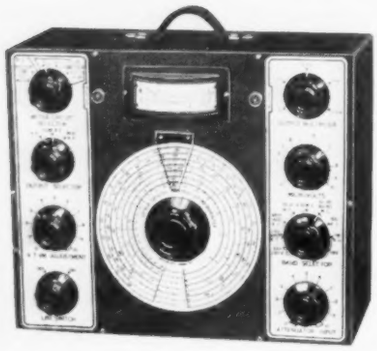

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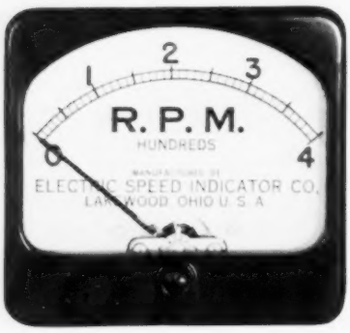

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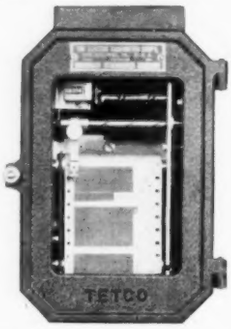

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Battery and Cable Voltmeter

New "Type DX-1" voltmeter, for testing automobile batteries and cables, may also be used for checking the voltage adjustment of relays, regulators and generators. Bat-

teries on a charging line, too, may be tested to determine completion of charge. Its accuracy is ±2%; its sensitivity 25 ohms per volt. Either single battery cells or an entire battery can be checked without removal from car. Twin binding posts allow optional connections for three- or nine-volt readings. Zeroing adjustment is located on back of case. *General Electric Co., Appliance & Merchandise Dept., Bridgeport, Conn.*

"Red-green-lights" Form of Car Battery Tester

For quickly determining if trouble exists in battery, starter, starting switch or cables, in a manner easily understood by car owners, new "Testlite" flashes either a red or a green light: it has no dial. By connecting two clips (one to starter terminal, the other to a ground on engine) test is made while turning engine with starter. If the red light flashes, an inspection of battery, wiring, etc., of starter circuit is required. If voltage is satisfactory, the green light will flash, to indicate that all units of starting circuit are in good condition. Instrument when being used is placed on fender or cowl, or may be held by its handle.—*Allen Electric & Equipment Co., Kalamazoo, Mich.*

Car Battery Tester

New "Batrecheck" is described as a "sensational new precision instrument" weighing 10 lbs. and permitting "making a rapid

analysis of the battery and the car's electrical system during the same operation."—*Kathanode Corp., 400 W. Madison St., Chicago, Ill.*

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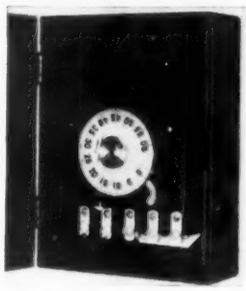
Send for Bulletin No. 105

RUBICON COMPANY
Electrical Instrument Makers
29 North 6th St. Philadelphia, Pa.

Automatic-reset Timers

A series of process timers is announced which, once set for a desired interval, permit starting by means of momentary-contact push-button. This starts timing motor,



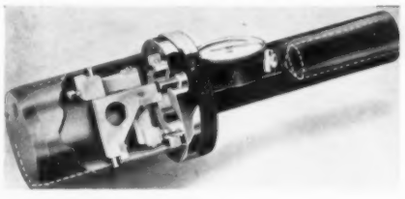
and dial begins rotating toward "0". On reaching this point timer performs specified function, shuts itself off, automatically recycles to starting position, and remains there until button is again pressed. In event of a current interruption, timers will automatically recycle, in readiness for the next operation when current resumes. Some units can be furnished which will not recycle if current is interrupted, but will remain in position and then complete the particular interval when current is restored. Timers are available for connection in series with an appliance: pressing button will start both appliance and timer; at end of interval, timer will shut off both appliance and itself, automatically recycle to starting position, and remain ready for next operation. Case dimensions 8½" × 6½" × 4".—*Automatic Electric Mfg. Co., Mankato, Minn.*

Combustion Safeguard

A smaller model of maker's "Flame-Otrol" combustion safeguard, designated as "Model 1101," has fewer contacts but incorporates same circuit and utilizes same flame-conduction principle. Control cabinet is 7⅝" wide, 10¾" high and 4½" deep, is available in surface- or flush-mounting styles. Contact load capacity: non-inductive rating, 10-amp. 110-volt, 5-amp. 220-volt.—*Wheelco Instruments Co., 1929 S. Halsted St., Chicago, Ill.*

Indicator Plug Gage

Reed mechanism utilized in maker's Visual Gage (see *Instruments*, Nov. 1938, page 238) has now been applied in the construction of a new indicator plug gage. Principal function of this gage is checking cylindrical bores during finishing operation, while they are still set up on machine, in order to determine the correct amount of machining. This gage, however, is equally useful for final inspection. It can be read to "tenths" and interpolated to fractional tenths. Reed principle is said to give this gage advantages not found in conventional plug comparators. It carries two diametrically opposed gaging points, freely moving in relation with each other. Thus any irregularity on either side of bore is indicated on dial and correctly evaluated; and effects of thrust pressure between part and gage are minimized. Another feature is ability to check a bore beyond a pilot sleeve which may be 0.001" smaller in diameter than bore itself. No pressure pads or wear strips are required.—*Sheffield Gage Corp., 1547 E. 3rd St., Dayton, Ohio.*



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Write for Bulletin 4201

Wheelco Instruments Co.
1933 So. Halsted St. Chicago, Ill.

Portable CO Indicator

New portable Model DS-14670 hand-operated carbon monoxide indicator employs same principle as maker's motor-driven pump type (*Instruments*, March 1935, page 83) but embodies a small 4-cylinder hand-operated pump and has otherwise been redesigned for lightness, its weight being 16 lbs. Sensitivity: scale range is 0-0.15% CO, reading directly to 0.005%. No connections to storage batteries or lighting circuits being required, instrument is safe to use where flammable gases are present.—*Mine Safety Appliances Co., Braddock, Thomas and Meade Sts., Pittsburgh, Pa.*

Tubeless "Single-tube" Manometer

Designed and constructed for withstanding pressures of newest boilers and individually tested at 4000 lbs./in.², new "Model A-306" manometer is of the "well" or "single-tube" type but the usual glass tube is replaced by a heavy rectangular bar of heat-treated shock-resistant glass, backed by a stainless-steel bar in which a groove serves as the "tube" for the mercury or other manometric liquid. Two channel members milled from steel bars further strengthen the device. Ranges: 15", 20", 30" and 40".—*The Meriam Co., 1955 W. 112th St., Cleveland, Ohio.*

Line and Cable Fault Location Test Set

At request of telephone engineers, "Type U" Test Set, used for cable fault location in signal and communication circuits, has been modified to permit use of the self-contained

galvanometer with the Hilborn loop: there has been added a switch position marked HIL. Because of its greater accuracy, the Hilborn loop is used for quickly locating faults in cable sections, particularly in metropolitan areas. Essentially, test set is a specialized self-contained Wheatstone bridge permitting use of Murray, Varley (and now Hilborn) loop-test methods; and used also in location of opens by capacitance methods. Weight approx. 8 lbs.; dimensions 8⅞" × 7⅝" × 5⅝".—*Leeds & Northrup Co., 4955 Stenton Ave., Philadelphia, Pa.*

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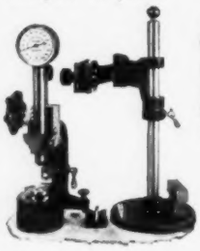

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Power Tap Switches

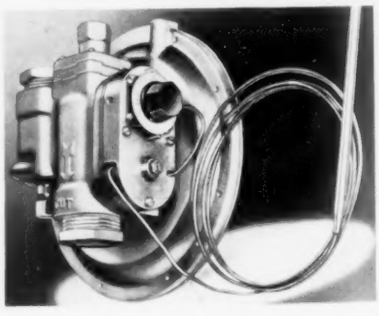
Three new models in addition to the 40-amp. tap switch recently announced (See *Instruments*, June 1939, page 156) now complete the series of maker's all-enclosed high-amperage tap switches. New units are multi-point, load-break, non-shorting single-pole, rotary selectors particularly designed for a-c. use. Contacts and mechanism are entirely enclosed and protected. Positive cam-and-roller mechanism provides "slow-break", quick-make action for a-c. shafts electrically "dead". Series now comprises 10-, 20-, 40- and 75-amp. resistors for 240-volt a-c. service.—*Ohmite Mfg. Co., 4835 Flournoy St., Chicago, Ill.*

Self-locating Bore Gage

Representing basic geometrical improvements over conventional star-gages, "Model 1200" cylinder or bore gage is of an entirely new design whereby three fixed (but adjustable) locating contacts locate the two measuring points diametrically and perpendicularly within the cylinder, thereby assuring centralization for any diameter throughout range of gage. Two models are available: 2⅞" to 5" and 5" to 10". Range of reading (of indicator) of each model is ±0.005". —*Federal Products Corp., 1144 Eddy St., Providence, R. I.*

Self-operating Temperature Controller for Gas Fuel

Either of two distinct modes of control is automatically selected by a new self-operating temperature controller known as "Modulating Gas Valve": (1) throttling mode throughout heating period and at all times



that demand requires valve to be more than nearly closed; (2) on-off mode when valve approaches closed position, and also with valve closed. Result is that before gas velocity is reduced to near flame velocity (i.e., before imminence of blow-back) valve suddenly closes; when temperature has dropped to low-point setting, valve is temporarily opened to full gas flow; and when normal-point setting is approached, throttling mode is resumed. Available ranges: 100-300°F., 100-500°F. and 300-600°F.; capacities 300 or 150 ft.³/hr.; standard capillary-tube length 6 ft.—*Wheelco Instruments Co., 1927-33 S. Halsted St., Chicago, Ill.*

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